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Modelling Chemically Enhanced Primary Settlers Treating Wastewater, using Particle Settling Velocity Distribution

Modellering av kemfällning i försedimentering för avloppsvatten, genom att använda distribuering av sedimentationshastigheter för suspenderade partiklar.

Emma Lundin

ABSTRACT

Modelling Chemically Enhanced Primary Settlers Treating Wastewater, using Particle Settling Velocity Distribution

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The urban sprawl creates a gap between producers and consumers and the a sustainable circuit of nutrients and energy is difficult to maintain. Many times the waste that is created in urban areas is not reused and the circuit is lost. In this project, wastewater treatment is looked at with the view point that resource recovery is possible through energy production and reuse of nutrients. In order to optimally run each process step at a wastewater treatment plant for improved resource recovery, more knowledge is needed in order to not disregard the final effluent quality. The goal of this project was to develop a model in MATLAB/Simulink for a chemically enhanced primary clarifier at a wastewater treatment plant. The potential of producing more biogas and reducing the aeration energy needed in the biological treatment step was looked at by focusing on describing the settling velocity of suspended solids. Experimental analysis on settling properties for solids was performed on sampled wastewater entering the primary settler after changing the addition of chemicals prior in the process line. The wastewater samples were homogenized and then rapidly vacuum pumped up in a column. The solids in the column could thereafter settle and was retained in a cup at the bottom. The mass of total suspended solids (TSS) was classified in five different settling velocity classes, each class assigned a characteristic settling velocity. The experimental procedure followed the ViCA's protocol (French acronym for *Settling Velocity for Wastewater*). A settler, much like the secondary settler in the Benchmark Simulation Model No. 2 (BSM2), a 10 layer non-reactive tank was modeled. The mass balance in each layer of the settler was decided by the vertical solid flux in the tank and built on the characteristic settling velocity gained from the experiments. Re-circulation of excess sludge from the subsequent steps at the plant showed to effect the settling properties of the sludge in the primary settler. The components of TSS showed to have the largest effect on the distribution of settling velocity. The variation in dose of both coagulant and cationic polymer prior the primary settling tank showed to effect the particle settling distribution somewhat. A first simulation with an applicable dynamic influent scenario was run. Despite any proper calibration the model gave fairly good predictions of measured TSS in the effluent and sludge outtake water.

Keywords: Modelling, Primary clarifier, Chemically enhanced clarification, Settling velocity, MATLAB/Simulink, Total suspended solids, Wastewater, Resource recovery

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REFERAT

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När urbana områden växer uppstår svårigheter i att bibehålla ett hållbart kretslopp av energi och näringsämnen. Avståndet mellan producent och konsument ökar och många gånger återanvänds inte det avfall som städerna producerar och det hållbara kretsloppet bryts. Detta projekt har fokuserat på resursåteranvändningen i avloppsvattenhanteringen genom möjligheterna som finns i energiproduktion i form av biogas samt återanvändning av näringsämnen genom slamåterförsel. Mer kunskap behövs inom varje processteg för att optimalt använda avloppsreningsverk för förbättrad resurs-återvinning så att inte utgående vattenkvalitet blir lidande. Målet med projektet var att utveckla en modell i MATLAB/Simulink för primärsedimentering med kemisk fällning. Experimentellt analyserades sedimentationsegenskaperna hos primärslam genom provtagning av avloppsvatten inkommande till försedimenteringen efter tillsatser av fällnings-kemikalier. Proverna homogeniserades och vakuumpumpades sedan snabbt upp i en kolonn. Det partikulära materialet i kolonnen kunde därefter sedimentera och fångades upp i en kopp i botten. Den sedimenterade massan av totalt suspenderat material (TSS) klassificerades i fem olika sedimenteringshastighetsklasser och varje klass tilldelades en karakteristisk sedimentationshastighet Det experimentella förfarandet följde ViCA’s protokoll (fransk förkortning för sedimentationshastigheter för avloppsvatten). En modell av en sedimentationstank, ungefär som för sekundär-sedimenteringen i Benchmark Simulation Model No. 2 (BSM2), utvecklades som en 10 lager icke reaktiv tank. Massbalansen i varje lager bestämdes av det vertikala flödet av partiklar och beräknades med de experimentellt framtagna karakteristiska sedimentationshastigheterna. Återcirkulering av överskottsslam från de efterföljande reningsstegen visade sig ha stor påverkan på slammets sedimentationsegenskaper i försedimenteringen. Typen av TSS-komponenter hade den största inverkan på fördelningen av sedimentationshastigheter. Variationen i dos av både fällningskemikalie och katjonspolymer före primär-sedimenteringstanken hade en viss påverkan på fördelningen. En första simulering med ett sannolikt dynamisk inflödesscenario kördes. Utan någon riktig kalibrering av modellen gav den ändå en relativt realistisk prognos på TSS i utgående vatten och i slamuttaget.

Nyckelord: Modellering, Föresedimentering, Kemisk fällning, Sedimentationshastighet, MATLAB/Simulink, Suspenderat material, Avloppsvatten, Resursåtervinning

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PREFACE

This project is a master thesis of 30 ECTS within the Master of Science program in Water and Environmental engineering at Uppsala University. Supervisors have been Robert Sehlén at Tekniska Verken in Linköping AB and Magnus Arnell at Urban Water Management AB. Subject reviewer was Bengt Carlsson at the Department of Information Technology, Division of systems and control at Uppsala University. Examiner was Allan Rodhe at the Department of Earth Sciences, Program for Air, Water and Landscape Sciences at Uppsala University. The project was developed in close collaboration with the modelEAU research group at Université Laval in Quebec City, led by Professor Peter Vanrolleghem.

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Emma Lundin

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Modellering av kemfällning i försedimentering för avloppsvatten, med hjälp av observerade sedimentationshastigheter

Emma Lundin

Urbaniseringen i Sverige, såväl som globalt, utmanar en miljömässigt hållbar livsstil. På en övergripande systemnivå blir det tydligt att näringsämnen och energi lämnar ett hållbart kretslopp. En utbredd urban miljö skapar avstånd mellan livsmedelproducent och konsument liksom mellan energiproducent och konsument. Ett tydligt exempel kan vara näringsflödet av fosfor och kväve som mestadels tillförs åkermark genom konstgödsel, grödorna transporteras till städerna och näringsämnena hamnar i det vattenburna avloppssystemet Istället för återföring av näringsämnen till åkermark blir sjöar och andra vattendrag recipienter för näringsämnen där stora problem genom övergödning blir följdförlopp. För att klara av den ökade belastningen av näringsämnen i avloppsnätet i urbana områden ställs allt högre krav på avloppsreningsverken.

Den här rapporten belyser möjligheten att behandla avloppsvatten inom ramarna av ett alternativt system. Avloppsvatten behöver inte bara vara en belastning för samhället att värja sig från utan är en bärare av näringsämnen och energi och bör ses som en resurs. Vad detta innebär och dess fulla potential är under utformning och diskuteras av forskare runt om i världen. Modellering av avloppsreningsverk för att utforska alternativa scenarior har en växande marknad i framför allt Nordamerika och är på inmarsch även i Sverige. Genom att skapa processmodeller av reningsverkens olika steg skapas möjligheten att titta på nya scenarion. Hur ser reningen ut om avloppsvattnet källsorteras, hur mycket energi kan sparas, var finns det potential att plocka ut det organiska materialet för rötning och var i processen tas näringsämnena ut för återanvändning fördelaktigt? Utifrån modeller ges möjligheten att utforma nya reglerstrategier för att uppnå de målbilder som uppkommer med ett övergripande system med alternativt fokus. I många av de svenska större städerna drivs stadsbussarna av biogas som producerats på stadens biologiska avfall. Flera reningsverk, exempelvis Nykvarns reningsverk i Linköping som använts som fallstudie i detta projekt, rötar sitt avloppsslam i anaeroba rötkammare och bidrar till stadens produktion av fordonsgas. Genom uppströmsarbete kan det rötade slammet REVAQ-certifieras och återföras till åkermark. Detta är ett relativt nytt system som växer fram där avloppsvatten ses som en resurs istället för en belastning.

Det största slamuttaget på ett vanligt svenskt reningsverk sker i försedimenteringen. Där avskiljs partikulärt material från vattenfasen och ofta tillsätts så kallade fällnings- och flockningskemikalier för att optimera processen. Olika metallsalter används vanligen för att fälla ut upplösta fraktioner av framför allt fosfor och bidrar även till att partiklar klumpar ihop sig för en effektivare sedimentering. Stora partiklar sjunker i flesta fall snabbare än mindre och lättare partiklar. I efterföljande biologiska reningssteg avskiljs traditionellt både organiskt och oorganiskt kväve genom denitrifiering och nitrifiering som sköts av aktiva bakterier. Kväve omvandlas till kvävgas som avgår till atmosfären. För att denna process skall fungera krävs tillförsel av syre och stora luftare monteras på bassängernas botten. Luftarna slukar den allra största andelen energi som används på ett reningsverk. Den organiska energi som kommer med avloppsvattnet används av bakterierna och avges som värme och koldioxid. Det är en möjlig resurs som går förbrukad samtidigt som förbrukningen av extern energi är hög.

Ett ännu större slamuttag i försedimenteringen avlastar den biologiska reningen och skapar mer slam för rötning och biogasproduktion.

Modellen för en försedimenteringsprocess som tagits fram inom ramarna för det här examensarbetet har byggts på experiment med avloppsvatten taget från den fullskaliga processen på ett avloppsreningsverk. Tre kemikalier doseras inför försedimenteringen. Målet var att dela in det sedimenterade slammet i olika klasser beroende på sedimentationshastighet Fördelningen av sedimentationshastigheterna berodde som väntat, av doseringen av fällnings- och flockningskemikalierna. Med en hög dos av fällningskemikalier ökade andelen av det partikulära materialet som sedimenterade långsammast. Lösta ämnen som fälldes ut till partikulärt material sedimenterade förhållandevis långsamt. Tendensen var att den långsammaste fraktionens sedimentationshastighet ökade något med ökad tillsats av flockningskemikalier. Det är viktigt för både optimerat slamuttag och minskad turbiditet i utgående vatten att fällningskemikalierna kombineras rätt. Modellen som utvecklades möjliggjorde testning av olika doseringsmängder för ett varierande inkommande flöde till reningsverket Avloppsvatten är mycket oförutsägbart och dess partikulära innehåll fluktuerar kraftigt under en dag. Med målet att öka slamuttaget bör varierad kemikaliedosering simuleras i modellen för att utvärdera försedimenteringens potential.

Att optimera processen är inte rättframt och tydliga strukturer för hur kemikalietillsatserna påverkar kunde inte ses för att säkerställa en helt tillförlitlig modell över försedimenteringen. Projektet ledde till att en dynamisk modell ändå togs fram som kan komma att användas och med ytterligare utveckling också inkorporeras i en modell över hela verket Mätmetoden som låg bakom de experimentella försöken är osäker men visar på viktiga tendenser för hur sedimenteringen påverkas. Med ytterligare experimentella försök kan troligtvis vissa osäkerheter klargöras.

Att se på avloppsvatten utifrån ett helhetsperspektiv där det räknas som en resurs är ett snabbt växande område inom forskningen. I detta arbete har både metod- och modellutveckling angripits. Det har lett till ökade kunskaper för processutvecklingen och ett steg i riktning mot ett alternativt synsätt på hanteringen av avloppsvatten.

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Smiles create smiles!

Table of Contents

Acronyms

WWTP	Wastewater Treatment Plant
PST	Primary Settling Tank
ASM	Activated Sludge Model
COD	Carbon Oxygen Demand
ViCA's	Vitesse de Chute Assainissement (Settling Velocity for Wastewater)
AST	Activated Sludge Tank
TSS	Total Suspended Solids
BOD	Biological Oxygen Demand
EPA	Environmental Protection Agency
BSM2	Benchmark Simulation Model No. 2
VSS	Volatile Suspended Solids
PLS	Partial Least Square regression
MLR	Multiple Linear Regression
PSVD	Particle Settling Velocity Distribution
FFD	Fractional Factorial Design
RST	Return Sludge Treatment

1 INTRODUCTION

With a growing majority of the world's population living in urban areas (United Nations data, 2012), the key is to develop sustainable energy use and reuse of nutrients and water within the urban community. Energy consumption at a wastewater treatment plant (WWTP) is linearly related to the size of the population connected to it (Plappally & Lienhard, 2012). Frijns et al. (2005) declared that to meet future water quality demands as the climate changes and reduce the environmental impact as well as the carbon footprint by efficient energy use, new concepts have to be developed. Water has to be viewed as a carrier of nutrients, carbon energy, heat and a source for renewable energy. Over the last five to ten years a shift has taken place towards this point of view when it comes to WWTPs. However, wastewater modelling has for long still focused on the effluent qualities, perhaps underestimating the possibilities given by modelling the onsite energy aspects and nutrient recovery. Heat recovery from WWTPs has been found to be very valuable and the energy source to possibly be greater than the demand on site, opening up for distribution of heat (Chae & Kang, 2013). Producing biogas offers WWTPs the opportunity to create energy and even become net energy producers. When the wastewater treatment plant is run to maximize biogas production in anaerobic sludge digesters, the primary settler serves as the most important sludge producer (Metcalf & Eddy, 2014). Bachis et al. (2014) recommend to reconsider the function of the primary settling tanks (PSTs) under the activated sludge model (ASM) framework as it may be of significance for the entire WWTP.

The primary treatment at a WWTP, including screening and removal of suspended solids is an overall low energy intensity process with primary sludge pumping being the most energy intensive part (Plappally & Lienhard, 2012). The primary treatment will however have a negative effect on the overall energy footprint of the facility if designed and operated poorly (Plappally & Lienhard, 2012). The aeration in the activated sludge treatment consumes significant amounts of energy and in addition the chemical energy in COD (Carbon Oxygen Demand) is lost as metabolic heat (Frijns *et*al., 2013). As more sludge is taken out from the primary settlers, the aeration in the activated sludge treatment can potentially be reduced. As Greenfield and Batstone (2005) concluded, the anaerobic digestion gives a great opportunity to decrease energy use and on top of that create a renewable energy source, biogas, maximizing the recovery of carbon energy in wastewater, see also Frijns et al., 2013.

In Linköping, Sweden, the production of heat from waste, biogas generation from organic compost or sludge as well as water treatment is all managed by the same operator, the municipal share company “Tekniska Verken AB”. There is an interest within the company to create sludge from the wastewater treatment plant that can serve the biogas production, utilized by the city buses and where the digested sludge can return to farmland for resource recovery.

The most important role of primary settlers at a wastewater treatment is to reduce phosphate, turbidity and particulate matter such as insect eggs, pathogenic bacteria and virus as well as waste products (Kemira, 2003). The turbidity in water increases when suspended particles have the same size as the wavelength of light, defined as colloidal material which will not settle without a coagulant. (Kemira, 2003). By adding coagulants in the primary clarifiers, the turbidity and particles can be reduced (Kemira, 2003). WWTPs are usually very large-scale processes where varying heterogenic water is treated. The chemical theory cannot tell us everything on how to optimally control primary sedimentation since the composition of the incoming water is difficult to predict. Instead the processes taking place in the PSTs can more accurately be described through knowledge about the actual particle settling distribution and process modelling (Bachis et al., 2003). Having a dynamic model gives the possibility to test different influent scenarios and control strategies for the PSTs.

1.1 OBJECTIVE

The goal for this master thesis project was to find a deterministic mathematic process model of a PST that is able to simulate a dynamic influent. The ambition was to build the model on experiments carried out at Nykvarn's wastewater treatment plant in Linköping, Sweden, using the ViCA's protocol (a French acronym for Settling Velocity for Wastewater). Evaluating the method behind the ViCA's protocol was also an objective in itself since the setup hasn't earlier been used for testing chemically enhanced settling. An overall aim was that the experimental part would improve the knowledge and understanding of chemical enhancement in the primary clarifiers.

1.2 DELIMITATIONS

The study was carried out during the summer months of May through September over a total of 20 weeks. All sampling and experimental analysis were done during dry-weather conditions and flow was considerably low. Only a restricted interval of chemical dosage was tested and the given model should primarily be used for similar conditions. The project was a site specific study at the wastewater treatment plant in Linköping.

2 BACKGROUND

At a modern WWTP the water treatment goals have to be met at the same time as the energy use is minimized. The primary clarification process is a low energy consuming treatment step and can through optimization be seen as an opportunity to relieve the more energy intensive treatment steps. At Nykvarn's WWTP an expansion with new lanes is limited due to the high cost of land. A growing population and restricted effluent emission rights means that the existing processes needs to be looked at in terms of optimization instead.

2.1 ENERGY USE AND PRODUCTION AT WWTPS

Biological treatment of wastewater in activated sludge tanks (ASTs) is universally used to reduce nitrogen. About 50 percent of the total energy consumed at a WWTP is spent on aeration in this process (Metcalf and Eddy, 2014). Furthermore the energy described as chemical oxygen demand, (COD) present in this stage will be lost through metabolic heat, creation of new biomass and emission of carbon dioxide (Frijns et al., 2013). However, with primary settling and sludge digesters generating biogas, a WWTP consumes on average 40 percent less energy than if sludge digestion was not applied (Frijns et al., 2013). Methane gas captivation in anaerobic digestion is the main source of energy at a municipal wastewater treatment plant (Tyagi & Lo, 2013).

To maximize sludge digestion, up-concentration of dissolved COD through settling, sieving and bio flocculation is commonly used. These processes are however energy consuming (Frijns et al., 2013) and the resulting wastewater after COD conversion will be rich in nitrogen. Greenfield & Batstone (2005) strongly highlights the importance of controlled anaerobic nitrogen treatment to conserve energy. Sharon, a nitrogen removal treatment for sludge, and Anammox systems together provide an energy-beneficial technology, avoiding aeration expenses (Frijns et al., 2013).

2.2 PRIMARY CLARIFICATION PROCESSES

When wastewater first reaches the treatment plant it most commonly passes through a course grid that physically removes larger particles. Before any other treatment, PSTs are primarily used to remove total suspended solids (TSS), reducing the load of phosphorous and biochemical oxygen demand (BOD) (Svenskt Vatten, 2010). The primary clarification gives the possibility to control the flow of energy and carbon source to the plant. Colloidal matter will only be removed in a settler if a flocculation aiding chemical is added so that aggregates form. The flocculent agent is added in a mixture tank and forms the “glue” that creates flocks and assists them to grow as the larger particles collides with smaller slow-settling particles (Metcalf & Eddy, 2014). Of the total phosphorous in the incoming wastewater, 50 to 80 percent enters in the form of orthophosphate, $H_2PO_4^-$ or HPO_4^{2-} depending on pH (Kemira, 2003) and a coagulant is needed for precipitation. Chemically enhanced particle settling enables a proficient clarification process.

Concentration of TSS and the tendency for particles to interact generates different types of settling. When a particle can fall freely without interference of other particles it is called *discrete settling*. *Flocculent settling* is when sinking particles aggregate and increase in size. This is typical for the settling found in primary settlers. When the concentration of particles is so high that it disturbs the procedure of sedimentation this is called *hindered settling* (Svenskt

Vatten, 2010). Hindered settling is not desired in a PST. *Compression settling* occurs as the mass of particles is consolidated from the weight of added particles (Metcalf & Eddy, 2014).
For chemical precipitation, aluminium or iron salts are added prior to the pre-clarifier, for precipitation of phosphorous and to create sweep coagulation by formed hydroxides (Svenskt Vatten, 2010). At the Linköping WWTP a chemistry system of three components is used, called FAST (a Swedish acronym for "pre-sedimentation of suspended material with triple dosage"). Initially a metal salt, ferrous sulphate *COP* delivered by Kemira is added to pre-coagulate colloidal matter. The ferrous sulphate is expected to oxidize to ferric oxide in aeration pools. A bit later in the process line a high-molecular cation polymer, Zetag 8180 is added to further coagulate colloidal material and eventually a high-molecular anion polymer, Zetag 4125, both delivered by BTC Europé GMBH, is added to create solid flocks (CIBA, 2006). This system aims to optimize the particle reduction (Sörensen & Larsson, 1992), creating stable flocks, enabling lower additions of metal salts and secondarily through higher sludge production facilitate a greater biogas production while alleviating the biological processes (CIBA, 2006). The coagulant used at Nykvarn WWTP is ferrous(II)sulphate, expected to oxidize to ferric(III)sulphate, $Fe_3(SO_4)_2$, in the maturation zone before entering the PST and therefore used in this section to explain the chemistry of chemical precipitation. As the metal salt, also called the coagulant, is added to water, polymer ions and hydroxides are formed in a chain reaction which can be simplified as:

$$Fe^{3+} + 6H_2O \rightarrow Fe(OH)_3 + 3H_3O^+ \quad (1)$$

With time the hydroxides form flocks and show a positive surface charge if pH <9.3 (Svenskt Vatten, 2010) and can therefore adsorb negatively charged compounds such as orto-phosphate (Kemira, 2003). However, direct precipitation of orto-phosphate by Fe^{3+} is shown a much more efficient separation method (Kemira, 2003). To increase the probability for the metal salt to react with the pollutants such as:

$$3\,Fe^{3+} + 2PO_4^{3-} \rightarrow Fe_3(PO_4)_2 \quad (2)$$

and not just with water, it is important that the mixing is very turbulent (Kemira, 2003). Also water temperatures effect the settling, lower temperatures require a longer retention time (Kemira, 2003). Summer temperatures in Sweden results in wastewater temperatures around 15-20 ˚C.

2.3 LINKÖPING WASTEWATER TREATMENT PLANT

Nykvarn WWTP in Linköping is run primarily to create an effluent that meet the Swedish Environmental Protection Agency's (EPA's) guidelines, in order to achieve the requirements that are addressed in the Swedish environmental legislation. The concentrations of BOD_7, total phosphorous, total nitrogen and ammonium may not exceed values presented in Table 1. The incoming wastewater to Nykvarn WWTP comes from the town of Linköping and surrounding smaller towns. The average total flow during a year is 1830 m^3/h (Tekniska Verken, 2013). The plant is built with integrated mechanical, chemical and biological treatment. Firstly larger particles such as rags, sanitary items and paper towels are removed with a mechanically cleaned screen. A sand trap further lets sand and similar particles to settled. Ferrous(II)sulphate is added to the inlet of the sand trap in a zone of turbulence. In pre-aeration tanks the ferrous iron is oxidized to ferric oxide and flocks form as described in section 2.2. Cation polymer is added prior the aeration zone. The third chemical enhancer, anion polymer is added right before the PSTs (Figure 1). Two round cone shaped PSTs gather the flocks towards the centre of the tanks facilitated by a moving scraper. The total primary

Table 1. Discharge permission imposed by the Swedish environmental court and achievements for the residual matter in the water leaving the WWTP (Tekniska Verken, 2013).

Parameters	Effluent limits	Achieved values
BOD_7	8 mg/l, quarterly average 130 tons per year	Monthly average <3-5 mg/l; <78 tons per year
Total phosphorous	0.25 mg/l, quarterly average 4.1 tons per year	Between 0.19-0.23 mg/l 3.0 tons per year (2013)
Ammonium nitrogen	2.5 mg/l, average for the total period June to October	2.0 mg/l average for June to October
Total nitrogen	12 mg/l, annual average 220 tons per year	11 mg/l, annual average 158 tons per year (2013)

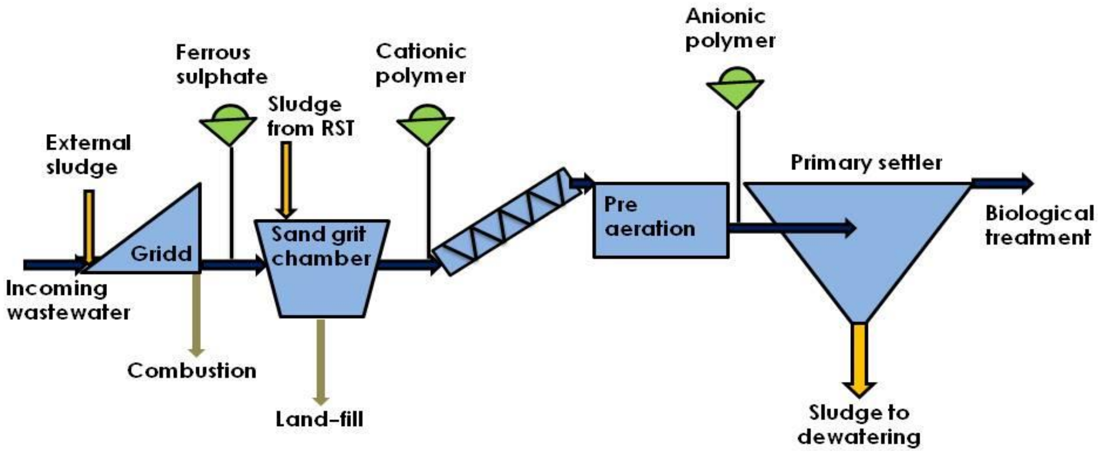

Figure 1. The mechanical treatment step at Nykvarn WWTP. (Tekniska Verken, 2013).

settling surface is 2600 m^2 (Tekniska Verken, 2012) and the retention time in each tank is abound 2 to 3 hours. The sludge from the PSTs is thickened, then for about 20 days treated in three anaerobic digesters, heated by district heating to a temperature of 37 degrees Celsius and then dewatered (Tekniska Verken, 2013). Nearly all the produced biogas is sold for vehicle gas production and the dewatered sludge residue returned to farmland. As of 2013 the total biogas production was 17 875 000 kWh (Tekniska Verken, 2013).

From the PSTs the water is lead to the biological treatment which is divided into three parallel lanes of activated sludge steps, alternating between aerated and non-aerated to facilitate both nitrification and de-nitrification to reduce nitrogen (Figure 2). At Nykvarn WWTP the energy consumption in aeration in this step is about 30 percent of the energy use at the entire facility (Sehlén, 2014). Next in the process line, secondary settling separates the bio-sludge from the water. A partial flow of the settler effluent, 1100 m^3/h (Tekniska Verken, 2013), is pumped to a post-denitrification process step with anoxic zones filled with a carrier material of type

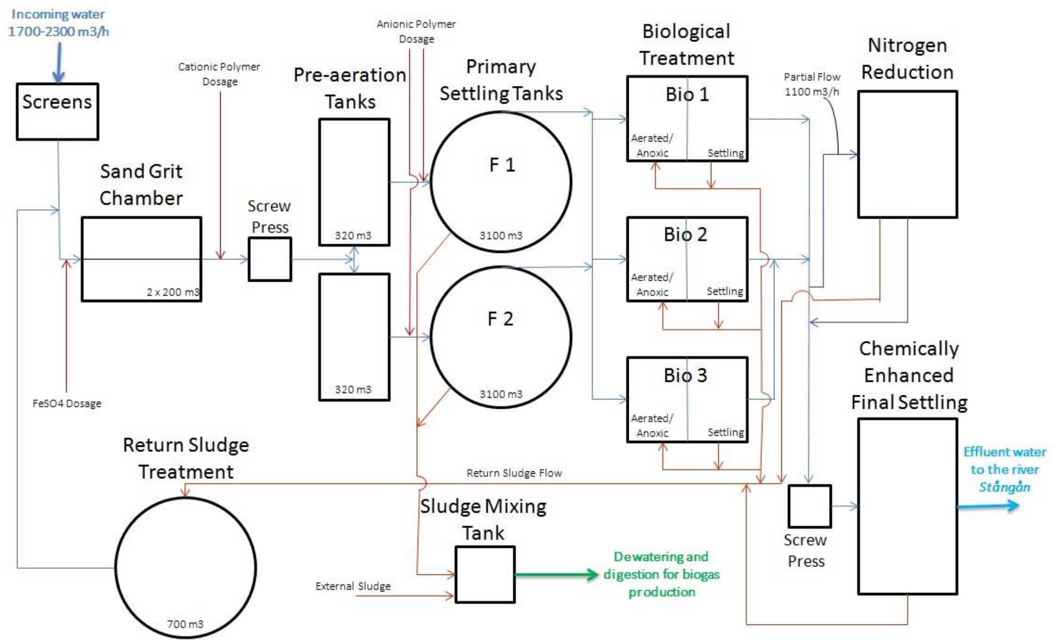

Figure 2. Nykvarn's WWTP has two primary clarifiers. Here seen as the round tanks of 3100 m^2 each. The figure does not display the sludge treatment steps including the Sharon tank.

Anox Kaldes K1 Heavy (Tekniska Verken, 2012). At this stage phosphoric acid and ethanol is added for enhanced de-nitrification.

The excess sludge from the secondary clarifiers, after the biological treatment step, is pumped back into the sand trap chambers, corresponding to about 20 percent of the TSS on an annual basis that enters the primary settlers and goes to the anaerobic digesters. Recirculation of excess sludge is a common procedure in Swedish WWTPs. The contribution of re-circulated sludge leads to the primary sludge having similar properties as active bio-sludge. The reject water from sludge centrifuges and screw presses used in the process line is reduced from nitrogen in a Sharon reactor. The excess sludge from the Sharon process is also pumped back to the PST inlet and makes up 2.5 percent of the sludge contribution (Sehlén, 2014). Finally in the treatment process line there is another step of chemically enhanced precipitation by aluminium chloride followed by sedimentation which further reduces the phosphorous concentration before the reject is let out in the recipient river, *Stångån*. The last chemically enhanced settling contributes to 1.2 percent of the sludge flow pumped back to the inlet. The return sludge from the secondary clarification, final chemically enhanced settling as well as reject water from the Sharon process goes through a return sludge treatment (RST), which comprises of an aeration tank with a 5 hour retention time, before pumped back to the sand grit chamber (Figure 1) (Tekniska Verken, 2013).

2.4 PARTICLE SETTLING THEORY

Separating solids from water, using gravity as force, is an important process at WWTPs. The difficulty in finding a model that can describe settling particles with different flocculent nature from one layer in the tank to another was addressed by Takács et al. (2001). Sufficiently low concentration of particles in the top layers of the clarifier results in discrete settling. However, Takács et al. (2001) further states that the solids tend to settle as a unit as the concentration of solids increases in the bottom layers. Hindered settling, likely to occur in the lower layers, has earlier been modelled using Vesilind's equation for settling solids, written as:

$$v_S = v_0 e^{-\alpha X} \quad (3)$$

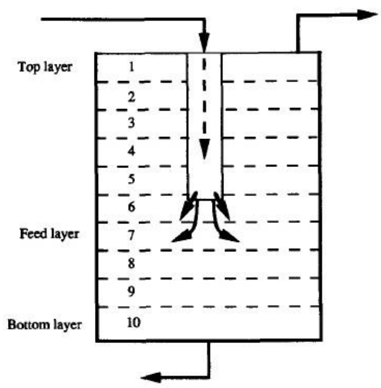

Figure 3. Layered settling model of 10 layers (after Takács et. al., 2001).

where v_S is the settling velocity of the suspension, v_0 is the suspension's maximally possible settling velocity, X the solids concentration and α a model parameter. In the mentioned publications, the secondary clarification tank was modelled as a 10 layer unit, each layer of constant thickness (Takács et al., 2001; Alex et al., 2008). Also the primary settler can beneficially be modelled in the same manner. Depending on each layer's position it can have the property of a top layer, feed layer or bottom layer (Figure 3). Also layers in between these layers have certain properties. The mass balance between every layer is calculated as the difference in load, $Q \cdot X$, of suspended solids entering and leaving each layer. The influent wastewater enters the tank from the middle and is distributed out in the tank through the feed layer. The effluent of the tank exits at the surface and will therefore cause a bulk movement with a somewhat horizontally direction. In models, such as BSM2 that is further explained below, only vertical flow has been considered and incoming wastewater is assumed to be completely mixed and homogenous.

2.5 BENCHMARK SIMULATION PLATFORM

The BSM platform is a simulation environment designed with a plant layout with influent loads, test procedures and evaluation criteria used as a reference simulation model (Alex et al, 2008), where the primary clarifier will be modelled in this project. The Benchmark Simulation Model No. 2 (BSM2) enables comparison and simulation of varying influents with the purpose to make an objective comparison of control strategies (Jeppson, 2009). The influent data file to the model contains 21 variables including many different forms of COD and nitrogen as well as alkalinity, temperature and suspended solids. There are 14 state variables in the ASM1 used in the activated sludge process of BSM2 (Table 2). The simulation code may be used for any control strategy in any simulation platform.

In the Benchmark platform and in many other attempts to simulate a WWTP including the primary settling, the PST is assumed to be a completely mixed tank, separating the effluent overflow of the tank from the primary sludge (Alex et al, 2008). This model is not complex enough to use for controlling the performance of the settler and does not take notice to any enhancement though chemical addition. There are many programs used to simulate processes at WWTPs. MATLAB is commonly used to design dynamic process models and the simulations can be visually drawn up as a box diagram in the complementary simulation program Simulink (Mathworks, 2014). In Simulink the hydraulics of the WWTP is modelled. A site specific model, "Linköpingsmodellen" has been developed by Arnell (2013) in MATLAB, based on the BSM2 model. The over-all plant is evaluated using the effluent quality index (EQI) weighing the index of all pollution loads: TSS, COD, BOD_5 and NO_X leaving the plant, as well as the operational cost index (OCI): the sum of all major operating costs in the plant (Gernaey et al., 2014; Flores-Alsina et al., 2014). In BSM2 as well as in

“Linköpingsmodellen” the model computes the change over time for 21 variables by default. The first 14, the state variables in the ASM, are presented in Table 2.

Table 2. The 14 defined constituents in the influent data file [g/m^3].

Variable	**Notation**
Soluble inert organic matter	S_I
Readily biodegradable substrate	S_S
Particulate inert organic matter	X_I
Slowly biodegradable substrate	X_S
Active heterotrophic biomass	$X_{B,H}$
Active autotrophic biomass	$X_{B,A}$
Particulate products arising from biomass decay	X_P
Oxygen	S_O
Nitrate and Nitrite nitrogen	S_{NO}
NH_4^+ + NH_3 nitrogen	S_{NH}
Soluble biodegradable organic nitrogen	S_{ND}
Particulate biodegradable organic nitrogen	X_{ND}
Alkalinity	S_{ALK}
Total Suspended Solids	TSS

3 METHODS

The objective was to find how the distribution of settling velocity of the sludge in the PST is affected by different chemical additives. This was done according to the ViCA's protocol (Chebbo & Gromaire, 2009). The ViCA's protocol is based on the principle of homogeneous suspension meaning that the solids are from start uniformly distributed over the entire height of sedimentation. The particles are then assumed to settle independently of each other, without forming aggregates and without diffusion, i.e. *flocculent settling.* Modelling control strategies for a WWTP can be difficult in the sense of evaluation and comparison which is stated by Alex et al. (2008). In this master thesis a mathematical deterministic model was developed and implemented in a computerized simulation platform. The incoming wastewater composition is unpredictable and the inline processes non-linear. The model is intended to work dynamically with the variability in the influent and chemical enhancement enabling improved control.

3.1 EXPERIMENTAL DESIGN

The experimental set-up followed factorial design, which is a frequently used method to investigate how the response changes, distributed on different effects, due to variations in experimental factors (Carlson, 1982). The experimental design aimed to answer the following questions, quoted from User Guide to MODDE (MKS Umetrics, 2014):

- Which factors have a real influence on the responses?
- Which factors have significant interactions?
- What are the best settings of the factors to achieve optimal conditions for the best performance of the process?
- What are the predicted values of the results for given settings of the factors?

The experiments in this study were set up to investigate the interaction between four factors influencing the settling velocity. The four factors state the three chemicals added prior to the PSTs at the WWTP, *1) ferrous sulphate,* $FeSO_4^{2+}$*, 2) anion polymer* and *3) cation polymer* as well as *4) the loading rate of solids*, assumed to differ between morning and afternoon which will be explained below.

Representative wastewater samples were taken from the PST at the Nykvarn WWTP in Linköping after changing the dosage of chemicals prior to the primary settlers. Sampling was done during both high and low loading rates entering the plant, further explained in section 3.2.2.

Table 3.The factors and each setting that was experimentally analyzed.

Factors	Low level (-)	High level (+)	Center Points (0)
Fe^{2+} (g/m^3)	5	15	10
Cationic polymer (g/m^3)	0.5	1.8	1.15
Anionic polymer (g/m^3)	0.05	0.15	0.10
Loading rate (time)	08:00	13:00	08:00/13:00

Continuous online measurements on incoming water to the plant by Norling (2007), have indicated what also the plant process engineer, Sehlén (pers.comment) has seen more recently, that low concentration of suspended particles and phosphate coincides with low flow rate. In the same manner it has been found that high concentration of suspended particles coincides with high flow rate. Therefore, sampling water with a low load of solids was done at 8:00 am when the incoming flow rate is known to be low. Samples representing a high load of solids were taken at 1:00 pm when the incoming flow rate has increased. The dose of each chemical was set at low and high (Table 3), defined according to the WWTP's capabilities. The upper limit was limited by the dosing pumps and how thick the solution could reasonably be made which was discussed with Sjögren (2014). The lower limit was set symmetrically to the upper limit around a mid-point, near the current functioning dosage at the plant.

Water samples were taken from primary settler nr 2, which has quite a stable sludge blanket. All samples were taken during dry summer weather conditions. Each experimental VICA's set-up was performed twice, one after another in order to secure the reproducibility of the method. The four factors were altered for "screening" purposes. In statistical analysis, screening is used for identification of important factors, to give information about which factors dominate and what their optimal range of setting is (MKS Umetrics, 2014). The response for the statistical analysis was chosen as the percentage of settled particles within each class which was of relevance towards the experimental goals. The experiments were set up to follow a two-level factorial design. With this means that each factor was set to a high and a low level.

Table 4. Experimental test chart developed with the software program MODDE, used for analysis following ViCA's protocol, 12 experiments where four were center points.

Experimental Name	**Run**	**Sampling Time**	**Coagulant [mg/l]**	**Anionic Pol. [mg/l]**	**Cationic Pol. [mg/l]**	**Results [%] 1**	**2**	**3**	**4**	**5**
N1:1 & N1:2	1	08:00	5	0.5	0.05					
N2:1 & N2:2	12	13:00	5	0.5	0.15					
N3:1 & N3:2	8	08:00	15	0.5	0.15					
N4:1 & N4:2	4	13:00	15	0.5	0.05					
N5:1 & N5:2	9	08:00	5	1.8	0.15					
N6:1 & N6:2	7	13:00	5	1.8	0.05					
N7:1 & N7:2	6	08:00	15	1.8	0.05					
N8:1 & N8:2	3	13:00	15	1.8	0.15					
N9:1 & N9:2	10	08:00	10	1.15	0.1					
N10:1 & N10:2	2	13:00	10	1.15	0.1					
N11:1 & N11:2	11	08:00	10	1.15	0.1					
N12:1 & N12:2	5	13:00	10	1.15	0.1					

A full factorial design in this case would result in 36 experiments (two levels and four factors give 2^4 experiments). A reduced experimental design, called Fractional Factorial Design (FFD) is of advantage due to fewer needed experiments. However, a much too reduced design will lead to effects being confounded and a model difficult to comprehend and draw any conclusions from. The model resolution is a measurement defining what effects shown in the model might be confounded with other terms (Umetrics, 2001). For screening purposes, a factorial design with resolution IV (roman numbers are traditionally used to mark the resolution) is recommended (Umetrics, 2001). With four factors, a FFD with 2^{4-1} experiments (8 experiments plus center points) was possible without main effects being confounded with two-factor interactions. These criteria meet the recommendations for screening purposes (Umetrics, 2001). Therefore, a test chart was developed after 2^{4-1} FFD with four center points (Table 4).

The performed experimental series was named N together with its number according to the test chart and if performed with column no. 1 or no. 2 (Figure 4). The performed run order was generated by MODDE. Apart from the 8 experiments given by the FFD, four center points were tested in order to test the method's reproducibility. In these four cases the dosage was set to a standard level at both low and high loading of solids. Also, experiments were performed on sampled wastewater without any added chemicals, N0:1 and N0:2. The resulting percentage of suspended particles settling within each class 1 to 5 after each executed experiment was filled in and evaluated through MODDE's statistical evaluation tools. The compilation and evaluation of the results will be further explained in section 3.2.4.

Figure 4. The ViCA's equipment at the WWTP laboratory. *Photo: Emma Lundin*

3.2 EXPERIMENTAL METHOD

The experimental part of the project was mainly carried out at the laboratory of the WWTP (Figure 4: see Appendix I for an equipment list). A ViCA's column was placed over a mixed tank leaving just enough space at the bottom to easily slide a cup underneath. Two such columns were run to secure the results, Column 1 started about 20 minutes after sampling and Column 2 after 50 minutes. Only one column could be started at a time.

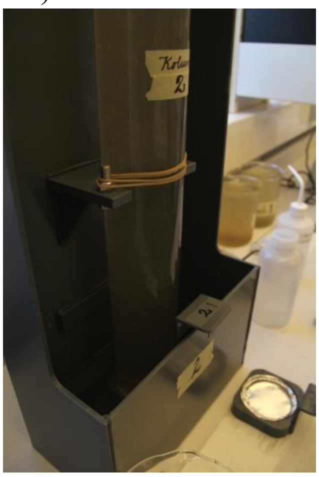

Figure 5. A cup was placed under the column, collecting the settled particles. *Photo: Emma Lundin*

The sampled wastewater was stirred; quickly poured into the mixing tank and vacuum drawn up into the ViCA's column in less than 5 seconds. The column was held under vacuum pressure for the whole duration of the test, 254 minutes. The settled particles were collected in a cup placed under the column with the same diameter as the latter (Figure 5). The cup was exchanged after gradually longer time periods, Δt= 2, 4, 8, 16, 64, 128. Filled with de-ionized water beforehand, a new cup was submerged into the tank and then positioned in under the column while the first cup was carefully pulled to the other side and emerged out of the tank. The contents of the cup was then filtered to make measurements of TSS and VSS on the recovered solids (see section 3.2.3). Collected mass was recovered and weighed continuously, which permits to determine the growth of the cumulative mass in the deposit *M(t)* as a function of time, *t*. In practice, the curve of the cumulative mass of solids that have deposited consists of *n* points, with *n* between 7 and 12, corresponding to the *n* samples taken after various times of settling. The particles are initially distributed homogeneously over the entire height of the column and they do not all fall the same distance. Consequently, *M(t)* does not correspond to a homogeneous class of particles.

3.2.1 ViCA's Calculations

The results of suspended particles settling in the column were evaluated according to the ViCA's protocol (Wipliez, 2010). The cumulative percentage, F(v_S) (in %) of total particle mass with a settling velocity below the settling velocity v_S (in mm s-1), was determined. F was derived from the adjusted function S(t), which is explained below. From experimental data on cumulative mass of particles that have reached the bottom of the settling column at t_i, the measured numerical value M(ti), was adjusted to a continuous function, given in equation

$$\mathrm{M(t)} = \frac{\mathrm{b}}{1+\left(\frac{\mathrm{c}}{\mathrm{t}}\right)^{\mathrm{d}}} \tag{4}$$

with the expression proposed by Bertrand-Karjewski (2001), used in earlier studies with ViCA's, with b,c and d being adjustment parameters minimizing the sum of squared errors through the least square method run in Excel (Chebbo & Gromaire, 2009). *S(t)* was calculated from *M(t),* considering the different fall heights. The mass of particles *S(t)* having a settling velocity $v_S > H/t$, was described as the adjusted function, *M(t)* subtracted by the particles settling from a height less than the column height, *H* (Chebbo & Gromaire, 2009).

$$S(t) = M(t) - t\frac{dM}{dt} \tag{5}$$

By combining (4) and (5) *S(t)* can also be expressed as (Chebbo & Gromaire, 2009):

$$S(t) = \frac{b\left[1+(1-d)\left(\frac{c}{d}\right)^{d}\right]}{\left[1+\left(\frac{c}{t}\right)^{d}\right]^{2}} \tag{6}$$

The settling velocity distribution curve, $F(v_S)$ where $v_S=H/t$ was finally obtained through:

$$F(v_S) = 100\left[1 - \frac{S(t)}{M_{tot}}\right] \tag{7}$$

where M_{tot} is the accumulated settled mass plus the mass remaining in the column at $t=t_N$ (Chebbo & Gromaire, 2009). The percentage of settled mass $F(v_S)/M_{tot}$ was plotted, with settling velocity on the logarithmic x-axis forming the characteristic ViCA's curve. For more detailed descriptions of the mathematical expressions behind the ViCA's protocol, see the article published by Chebbo & Gromaire (2009).

The settling velocity distribution was in this study chosen to be covered by five particle classes (Bachis et al., 2014) each given a fraction of the incoming TSS. Each particle class was identified by the settling velocity minimum, $v_{S,min}$ and the settling velocity maximum $v_{S,max}$ for that fraction of TSS. The class specific settling velocity, v_S was calculated as the geometrical mean of $v_{S,min}$, and $v_{S,max}$.

3.2.2 Sampling and Sampling Preparation

Figure 6. Primary settler nr. 2 at the WWTP when it was emptied and cleaned. Visible are the distribution pipes out from the middle. *Photo by Robert Sehlén.*

Two times five liters of wastewater for each experiment was sampled using a beaker on a stick. The wastewater was taken from inside the round cemented middle of the PST at Nykvarn's WWTP where the wastewater enters the tank. Here the turbulence is high and the wastewater well mixed. At each sampling time the dosage of chemicals had been changed an hour before hand according to the experimental design. The PSTs have a lag of about 45 minutes from the first addition of chemicals which makes an hour sufficient for an effect to show. The wastewater enters the PST in the middle of the tank. It is discharged tangentially through numerous pipes, 1 and 1.8 meters below the surface (Figure 6).

When using un-diluted primary wastewater in the ViCA's columns, hindered settling was observed and therefore the amount of measured TSS in the cup did not represent all the actual settled particles. To avoid the effect of hindered settling and losing settled mass in the test, the sampled water was diluted. A dilution of 1:2 or 1:3 with effluent water from the plant proved to be a suitable measure. The plant effluent was assumed to have similar composition of soluble compounds but not contribute to an increased particle load. Daily collected samples are weekly combined and analyzed for phosphate concentration at the plant laboratory. This data was used to evaluate the resulting phosphate concentration in the column after the experiment was finished.

3.2.3 TSS and VSS Analysis

The analysis of TSS and VSS followed the standard method SS-EE 872:2005 and SS 028112, with a measurement uncertainty of 15 percent in the measurement range of >2.0 mg/l and 30 percent in the measurement range of 0.1- 99% (of suspended particles) respectively. The content in each emptied cup was vacuum filtered through a 2.0 µm filter allowing dissolved solids to pass through and the suspended solids to remain on the filter. Each filter used in the TSS and VSS analysis was weighed before (m_0) and after letting the filter and residue dry in 150 ˚C for the minimum of an hour (m_1). The TSS concentration, in *mg/l*, was obtained by calculating the difference between the weight of the filter before and after filtration divided by the filtered volume:

$$TSS = \frac{(m_1 - m_0 - L) \cdot 1000}{V} \quad (8)$$

where L is the filter loss, lost weight when the filter dries in an oven. The VSS concentration was calculated by letting the filter and residue incinerate in a 550 ˚C oven for at least 2 hours, (m_2), and calculating the weight difference when the organic compounds had been combusted:

$$VSS = \frac{(m_1 - m_2 - L) \cdot 1000}{V} \quad (9)$$

The filter loss, L, is continuously calculated when opening a new batch by the laboratory staff according to the standard method SS-EE 872:2005 (for the analysis of TSS) and SS 028112 (for the analysis of VSS). In this study the median value of the calculated filter losses for the last 30 batches was used. The filter loss used for the 150 ˚C oven was calculated to 0.01 mg and the filter loss in the 550 ˚C oven to 0.08 mg.

3.2.4 Compilation of Results

Data compiled from TSS and VSS measurements from all experiments were accumulated on spread sheets developed by Jan-Luk Bertrand-Krajewski at the laboratory of civil- and environmental engineering at INSA in Lyon. From this spread sheet the ViCA's curves were calculated. The five particle classes[1] (Bachis et al., 2014), each assigned a fraction of the influent TSS (Table 5), were calculated from the ViCA's curves attained from each experimental set-up. The boundaries between the five classes were in a first evaluation of the results chosen the same as of an earlier experimental set-up by Maruéjouls (pers. comment). As the first 12 ViCA's analyses where done in duplicates, the overall experimental response was evaluated through looking at both duplicates, or only Column 1 or only Column 2. Also if any abnormal event occurred during any part of the sampling, settling or analysis, the data was not used as a response. For each experiment the mass balance in the column was calculated as the initial TSS in the wastewater minus the settled TSS and the remaining TSS in the column. A deviating mass balance of maximum 15 percent was accepted.

The responses, the distribution of the ViCA's curves from all experiments were evaluated with the software program MODDE 10.1 (MKS Umetrics, 2014). The results were statistically tested with Partial Least Square regression (PLS) and complemented with Multiple Linear Regression (MLR) to evaluate if the resulting class distribution was a statistically significant result due to the tested factors. Also which factors were important in order to model the outcome in MATLAB were eventually concluded. The statistical model was evaluated through the summary of fit parameters:

R2- measure of fit to the data; an R2-value less than 0.5 describes a model with rather low significance.

Q2- describes how well the model predicts new data. It is low when experimental errors are poorly controlled or model is incorrect; should be greater than 0.1 for a significant model.

Validity- measures if the model error is in the same range as the measurement errors.

Reproducibility- ability to give the same response under the same conditions.

[1]Five particle classes have been used successfully for primary settler model development before.

Table 5. The distribution of settling particle velocity was divided into five classes with the limits shown in the table. This division is a first guess for an implementation of the settling velocities in a model.

	Lower limit [Vs]	Upper limit [Vs]	Mean velocity [m/h]	Mean velocity [m/d]
Class 1	0.00010	0.16	0.004	0.096
Class 2	0.16	0.27	0.208	5.00
Class 3	0.27	1.25	0.583	14.00
Class 4	1.25	1.60	1.417	34.00
Class 5	1.60	18.91	5.500	132.00

PLS is suited for modeling a data set if there are several correlated responses, the experimental data has a high condition number and there are small amounts of missing data in the response matrix (Umetrics, 2001). It is an useful method for relating the factor matrix X and the response matrix Y to each other especially when data contains many noisy, collinear and incomplete variables in both X and Y (Erikson et al., 2006). The model provides a description of how both factors and responses interact. PLS components were calculated by MODDE, such that it well approximated the point-swarm in X and Y matrixes (Erikson et al., 2006). A score scatter plot was obtained by projecting each observation onto the PLS components which provides the correlation structure between the variations in factors and the responses (Eriksson et al., 2008). The linear summary of the response matrix Y, called u_1, is plotted against the linear summery of the factor matrix X, called t_1, which will ideally line up all the samples on the diagonal in a score plot (Eriksson et al., 2008). Any data point remotely placed from the diagonal might be an outlier (Eriksson et al., 2008). An interpretation of the PLS model is the loading scatter plot which shows the "importance of the X variables in the approximation of the Y matrix" (Erikson et al., 2006). The further away an X- or Y-variable lies from the plot origin the stronger that variable impacts the model. A PLS model of the experimental results was used as a first overall evaluation.

Multiple Linear Regression (MLR) is however more suitable for fitting data when wanting to custom fit the model. The statistical model was custom fitted to the data set, checking for outliers and interaction terms. The regression is computed through minimizing the sum of squared deviations between observed and fitted data. Both PLS and MLR were used in the evaluation of the experimental data. When deciding on a mathematical expression to calculate the distribution of settling velocity classes the customized regression coefficients from the MLR model were used.

3.3 MODELING METHOD

Gained knowledge about the settling velocity distribution in the primary settling tanks was used to upgrade the already existing "Linköpingsmodellen", i.e. The Linköping model, developed by Arnell (2013). The model calculations were done with MATLAB and the dynamic flow was calculated and presented in the MATLAB-based simulation program Simulink.

The pre-clarification script was based on the original c-file, settler1dv5_bsm2.c, used in the original BSM2 for the settlers after the activated sludge treatment. This model of a settler divides it into ten layers, *m,* of constant thickness predicting the sludge concentration through mass balance around each layer. In BSM2 a double exponential settling velocity function describes the settling in the secondary clarifier as (Takács et al., 1991):

$$v_S(X_{SC}) = \left[0, min\left\{v_0^{'}, v_0\left(e^{-r_h(X_{SC}-X_{min})} - e^{-r_p(X_{SC}-X_{min})}\right)\right\}\right] \tag{10}$$

where X_{SC} is the total sludge concentration. The equation expresses that the settling velocity is zero when the concentration is very low. At a concentration threshold, the settling velocity then reaches $v_0^{'}$, the maximum settling velocity. If the concentration of suspended solids is even higher hindered settling occurs and is here described by Vesilind's settling velocity expression, eq.). As for primary clarifiers, hindered settling is not desirable. Instead of using the settling model built on sludge concentration and assumed hindered settling eq. (10) the idea of this project was to use the fractions of TSS given specific settling velocities in the settling model. The net flux $J_S + J_{SC}$, of particles will be due to gravity and bulk movement, where J_S is calculated as

$$J_S = v_S(X_{SC})X_{SC} \tag{11}$$

and v_S will be determined experimentally. The gravitational flux in one layer of the dynamic model will be set to the same gravitational flux calculated in the layer above when flux is higher in the upper layers. The bulk movement, J_{SC}, is a result of upwards and downwards flow velocities. For the layers below the feed layer the bulk flow is calculated as

$$v_{dn} = \frac{Q_{SC,u}}{A} \tag{12}$$

where $Q_{SC,u}$ is the underflow of the tank. The flux is then proportional to the sludge concentration in the layer just above the layer looked upon. For the layers above the feed layer the bulk flow is calculated as

$$v_{up} = \frac{Q_{SC,e}}{A} \tag{13}$$

where $Q_{SC,e}$ is the effluent from the top layer of the tank. The layers have different properties depending on their position relative to the feed point. There are, as mentioned earlier, five types of layers: top layer, feed layer, bottom layer and layers in between these layers, numbered from up to down (again see Figure 3). The concentration of sludge in each layer is written as in BSM2 (Alex et *al.,* 2009). Mass balance in the feed layer is written as:

$$\frac{dX_{SC,m}}{dt} = \frac{\frac{Q_f X_f}{A} + J_{SC,m-1} - X_{SC,m}(v_{up} + v_{dn}) - min(J_{S,m}, J_{S,m+1})}{z_m} \tag{14}$$

where the first term is the incoming solid flux. For the layers below the feed layer and above the bottom layer the mass balance is written:

$$\frac{dX_{SC,m}}{dt} = \frac{v_{dn}(X_{SC,m-1} - X_{SC,m}) + min(J_{S,m}, J_{S,m-1}) - min(J_{S,m}, J_{S,m+1})}{z_m} \tag{15}$$

For the layers above the feed layer and below the top layer the mass balance is written:

$$\frac{dX_{SC,m}}{dt} = \frac{v_{up}(X_{SC,m+1} - X_{SC,m}) + J_{SC,m-1} - J_{SC,m}}{z_m} \tag{16}$$

under the circumstances that the concentration of sludge is greater in the level below the regarded layer, which is the case in a well working settler. If a sudden load of sludge enters the tank this might change the relationship and $X_{SC,m} > X_{SC,m+1}$. For the top layer (m=1), feeding the effluent the mass balance is written:

$$\frac{dX_{SC,1}}{dt} = \frac{v_{up}(X_{SC,2} - X_{SC,1}) - J_{SC,1}}{z_1} \quad (17)$$

The bulk flux, $J_{SC,1}$ is the net solid flux in the top layer. For the bottom layer (m=10), sludge take out, the mass balance is written as:

$$\frac{dX_{SC,10}}{dt} = \frac{v_{dn}(X_{SC,9} - X_{SC,10}) + min(J_{S,9}, J_{S,10})}{z_m} \quad (18)$$

With the knowledge from the ViCA's experiments on the distribution of settling velocity classes depending on chemical dosage, the solid mass balance around each layer was calculated for the 5 classes using the settling velocities, $v_{S,i}$. The model state variable TSS was divided into the five TSS classes through a function of load and the three added chemicals.

3.3.1 Model Validation

At Nykvarn WWTP, the laboratory staff perform weekly analysis on combined daily water samples after several of the process steps. The TSS concentration in the effluent from the primary clarifier is one of the measured parameters. Measured data from the facility was used to evaluate the modeled effluent. A likely dynamic influent scenario at Nykvarn's treatment plant was simulated with varying dosage of chemicals added in the model and results were compared with experimentally measured data and existing online data, to evaluate the model's feasibility (Table 6).

Validation parameters	
Plant influent	**Primary settler effluent**
Total Suspended Solids (TSS)	Total Suspended Solids (TSS)
Ortho-phosphate (Ortho-P)	Orto-phosphate (Ortho-P)
Total Phosphorous (Tot-P)	Total-phosphorous (Tot-P)
Total Organic Carbon (TOC)	Phosphate
Biological Oxygen Demand (BOD7)	Biochemical Oxygen Demand (BOD7)
	Turbidity (online)

Table 6. Regularly measured wastewater constituents at Nykvarn's WWTP possible to use for model validation.

4 RESULTS AND DISCUSSION

The sampled water was taken during dry weather at low and high flow to represent when the suspended particulate load entering the WWTP is high and low. Half of the experiments were taken at 8:00, from now on called morning samples and half were taken at 13:00, from now on called afternoon samples. All experiments were conducted during the summer months June to August. Therefore they represent an overall low loading rate compared to the rest of the year reflecting the activity in the town of Linköping which declines during periods of summer vacation. The results did however not differ as clearly as expected between morning and afternoon and the analysis showed little difference in initial TSS concentration.

4.1 EXPERIMENTAL DATA

The morning samples gave merging ViCA's curves (Figure 7) while there was a larger spread amongst the afternoon samples (Figure 8). The altering of chemical dosage prior to the PST at Linköping WWTP changed the settling velocity for the slowest settling particles with roughly 10 percent (Figure 7 and Figure 8). The experiment N10:2, was completely removed from further use due to unsatisfactory mass balance, i.e. larger deviation than 15 percent. N0:1, N0:2, N7:3, N9:3 and N10:3 were all performed after and outside the original test chart to complement the first results. The resulting curves from N0, when no chemicals were added at all were well embedded amongst the rest of the 8:00 am samples (Figure 7).

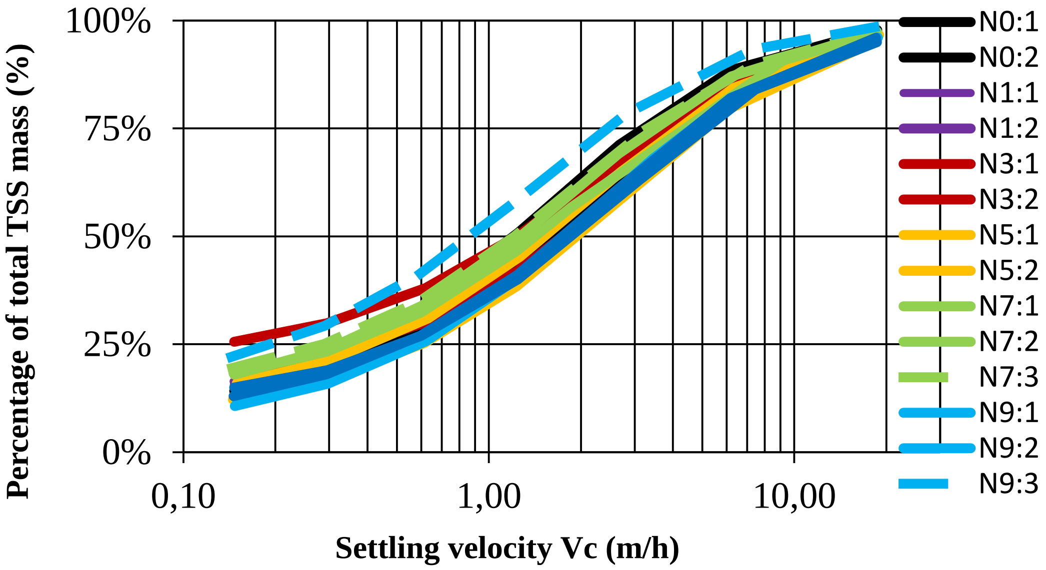

Figure 7. The ViCA's curves, $F(v_S)$, gathered from the morning samples with altering dosage of chemicals, compare with These criteria meet the recommendations for screening purposes (Umetrics, 2001). Therefore, a test chart was developed after 2^{4-1} FFD with four

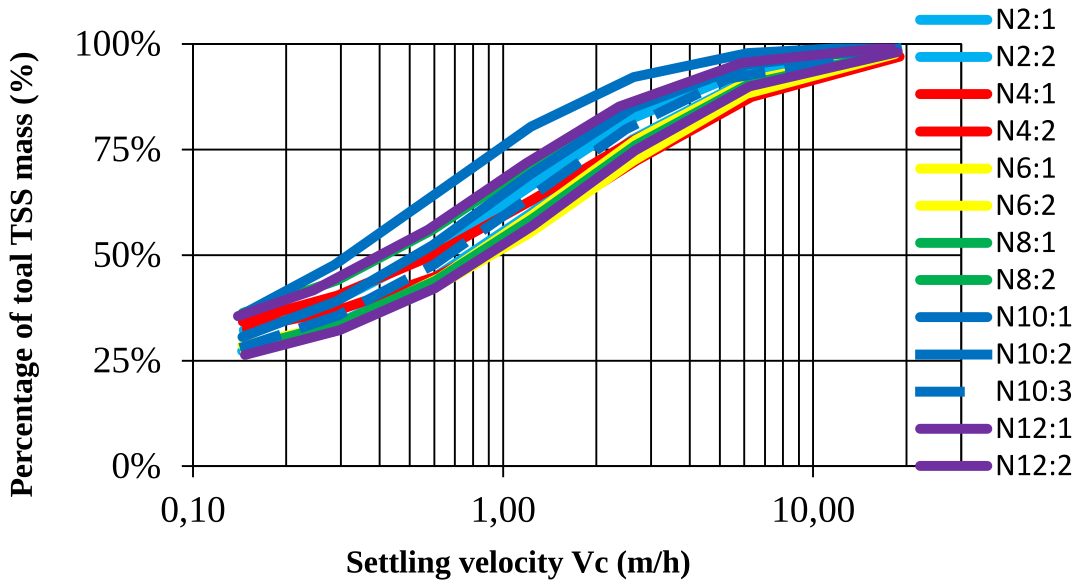

Figure 8. The ViCA's curves, $F(v_S)$, gathered from the afternoon samples with altering dosage of chemicals, compare with These criteria meet the recommendations for screening purposes (Umetrics, 2001). Therefore, a test chart was developed after 2^{4-1} FFD with four center points (Table 4).

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In order to find common denominators that provide the differences in the established ViCA's curves, a few first comparisons were done:

- Initial TSS concentration in the experiments did not as anticipated, differ clearly in "high" and "low" TSS load between the morning and afternoon. Most likely the TSS composition is the deciding factor, not the concentration. This will be further discussed in the section 4.1.1.
- A plot of percentage mass that has settled (y) with the n=7 calculated velocities from the VICAS spread sheet depending on TSS concentration (x) revealed that the concentration does not show a clear effect on the velocities.
- Differences in results between Column 1 compared to Column 2 was looked at and can be explained either by the storage time after sampling or the instruments themselves. Column 1 had a much more distinct division between morning samples and afternoon samples.
- The difference between the resulting ViCA's curves due to altered time between sampling and experimental start was not substantial. The difference fluctuated in both directions or was nearly absent (see Figure 9).
- In all the experiments where the duplicates differed from each other, there was a noticeable amount of sludge observed floating in the column initially. This addition creates an unidentified amount of sludge that will settle miscellaneously.

The ViCA's protocol was shown to be functional for chemically enhanced primary settling when diluting the wastewater. If not diluting the samples taken from the primary settlers, the flocks settled quickly, creating a thick sludge blanket and hindered settling occurred. Gelatinous properties of the settled chemical sludge was observed and described as a consequence of re-circulated secondary sludge as well as the chemical addition of a coagulant and polymers. Re-suspension of the fluffy sludge layer was to a varied extent observed as the cups were removed after 2, 6 and 14 minutes. This was initially observed with primary wastewater dosed with 5 mg/L coagulant, 0.5 mg/L cation polymer and 0.05 mg/L anion polymer (experiment N1:1, non-diluted). Therefore the measured TSS-content in the cup did not represent the amount of sludge that had actually settled, which lead to the dilution procedure already mentioned in section 3.2.2. The dilution was in most cases made 1:2 in Column 1 and 1:3 in Column 2. Bel Hadj (2003*)* showed that with dilution the settling velocity decreases, explained by the fact that at high concentrations the particles are more likely to collide with other particles and therefore drag down also smaller particles. In an experiment the median settling velocity decreased from 2.2 m/h to 0.2 m/h after a dilution of three times (Bel Hadj, 2003). The ViCA's protocol was ultimately concluded by Bel Hadj (2003) to be reproducible for diluted samples. These results imply that the ViCA's curve for a more diluted sample will likely be above the ViCA's curve for a non-diluted sample. This was seen in some cases but not in all and cannot be clearly concluded.

Each experimental set-up was performed twice with the same dosage of chemicals and sampling time. One difference was the time that the sampled water was kept in a plastic container before poured into the ViCA's tank. The second ViCA's was started around 30 minutes after the first. Compare for instance N3:1 and N3:2 (Figure 9), positioned on either side of the rest of the curves. To evaluate what effect the storage time could have, also the dilution was kept the same. Only N3:1 and N3:2 differ substantially from one another and this might be explained by uncertainties in the experimental performance.

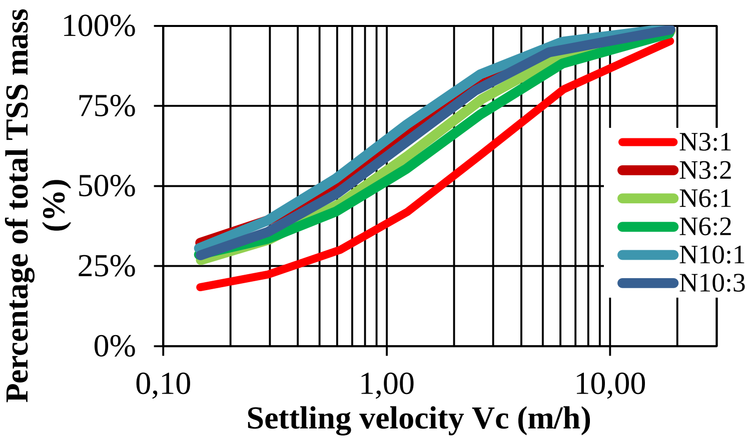

Figure 9. The resulting ViCA's curves in three cases when the dilution was made the same in Column 1 and Column 2 in order to evaluate the effect of storage time.

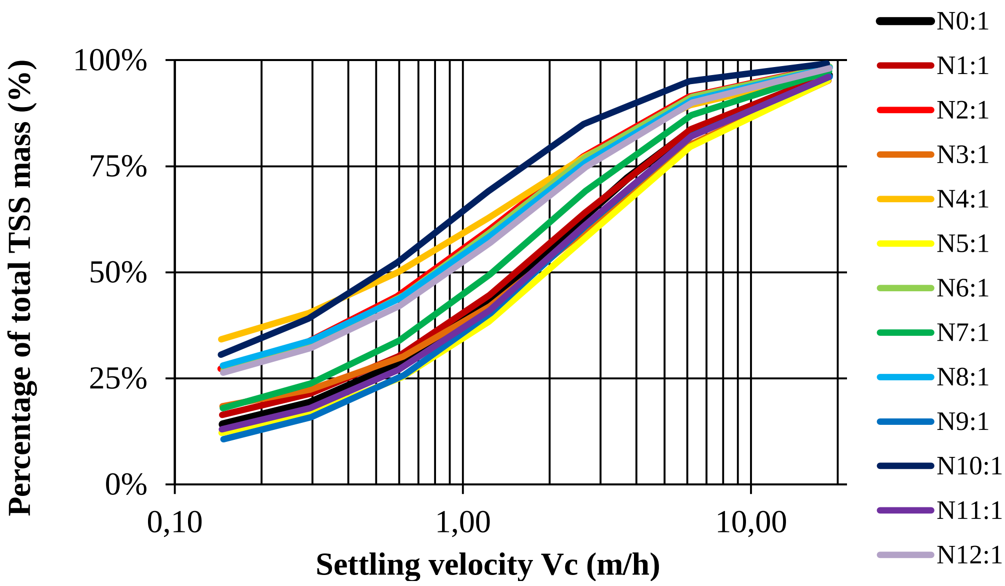

Figure 11. The settling velocity distribution, ViCA's curves, attained from Column 1. The top cluster of curves represent the afternoon samples and the bottom cluster of curves the morning samples.

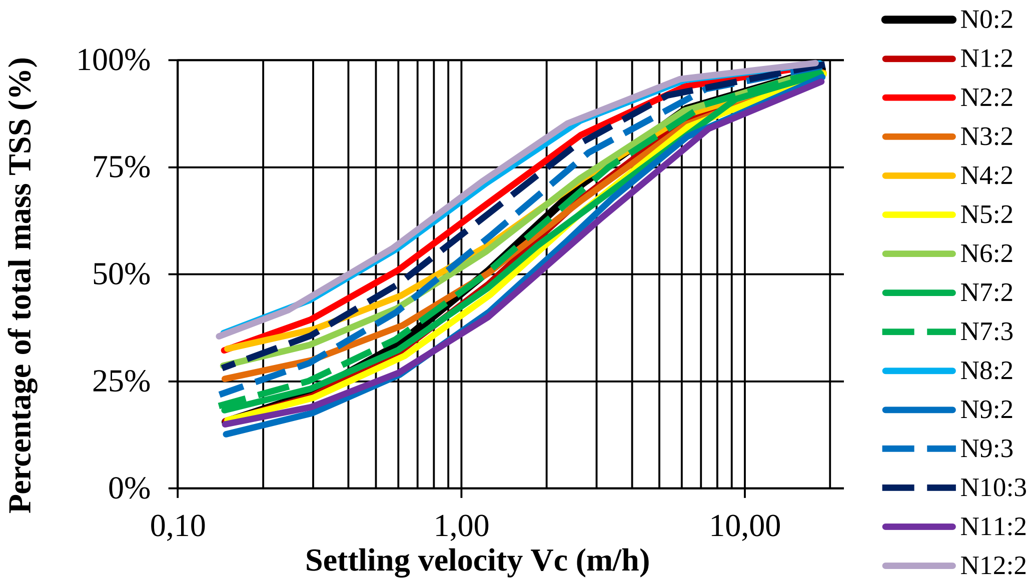

Figure 10. The settling velocity distribution, ViCA's curves, attained from Column 2. The top cluster of curves represent the afternoon samples and the bottom cluster of curves the morning samples.

4.1.1 TSS Mass Balance

The incoming wastewater to the plant had an average sludge concentration of 276 mg/l during the sampling period while outgoing average was 124 mg/l (combined 24-hours samples analyzed weekly by the WWTP laboratory). However, the initial TSS concentration of the sampled water differed between 435 mg/l and 654.4 mg/l in the experiments. The average TSS in the morning samples was 530 mg/l and in the afternoon samples 525 mg/l, meaning that the addition of re-circulated waste sludge in an average scenario contributes to almost half of the sludge concentration in the primary settler. Also the chemical sludge, created with

the added ferrous sulphate, is estimated to contribute to about 1 percent of the sludge flow. The relatively high and steady TSS load is a result of waste sludge from the process line fed back to the sand trap. The recirculation of excess bio-sludge is the greatest contributor to this flow. The excess sludge flow from the activated sludge tanks is controlled against the effluent TSS in the secondary clarifier and will depend on the degree of sludge compaction due to the bacterial growth.
Even if the difference in TSS concentration was not significant between the samples taken at 8 am and 1 pm, the ViCA's curves differed considerably between morning and afternoon (Figure 7 and Figure 8). The flow was close to double in the afternoon compared to the morning. In the morning between 6:30 and 7:30 (sampling at 8:00) the median value of the flow entering the WWTP was 1000 m^3/h and at noon the median flow was 2300 m^3/h (sampling at 1 pm). The differences seen between morning and afternoon sampling were probably a result of varying composition of TSS. Clearly, the degree of re-circulated sludge in the wastewater plays a critical role.

Interestingly there was a more distinct difference between morning and afternoon sampling in the data compiled from Column 1 (Figure 11). There was a slight difference in equipment between the set-up for Column 1 and 2. A somewhat bigger cup collecting the settling particles in Column 1 might have decreased the risk of re-suspended particles in the column and lead to a more reliable result from Column 1. The data collected from Column 2 showed that results from morning and afternoon were more or less entwined (Figure 11). The same type of curves were also developed for the VSS contents collected from the ViCA's cups. Since the VSS curves followed those of the TSS they are not presented in the report and not used in the development of the resulting MATLAB model.

4.2 STATISTICAL ANALYSIS

4.2.1 PLS Analysis

As a general analysis evaluation of the results a PLS model was evaluated with the software program MODDE. For this first approximation, the seven velocities (Table 6) from the ViCA's spread sheet were used as the responses in the factorial design. The fraction of settled TSS was estimated to the plotted data points from each ViCA's curve unless the cup had been changed at a strictly deviating time, *t*, then the settled fraction was calculated by the linear interpolation between two data points. The factors evaluated in the model was coagulant, cation and anion dosage. Instead of TSS load, the water flow was used to represent either the morning sample or afternoon sample, 1000 m^2/h in the morning and 2300 m^2/h in the afternoon.

Table 7. The ViCA's curve is created by plotting seven points representing the percentage of settled mass at corresponding settling velocities.

Seven calculated velocities creating the ViCA's curves [m/h]						
18.6	6.2	2.7	1.2	0.6	0.3	0.1

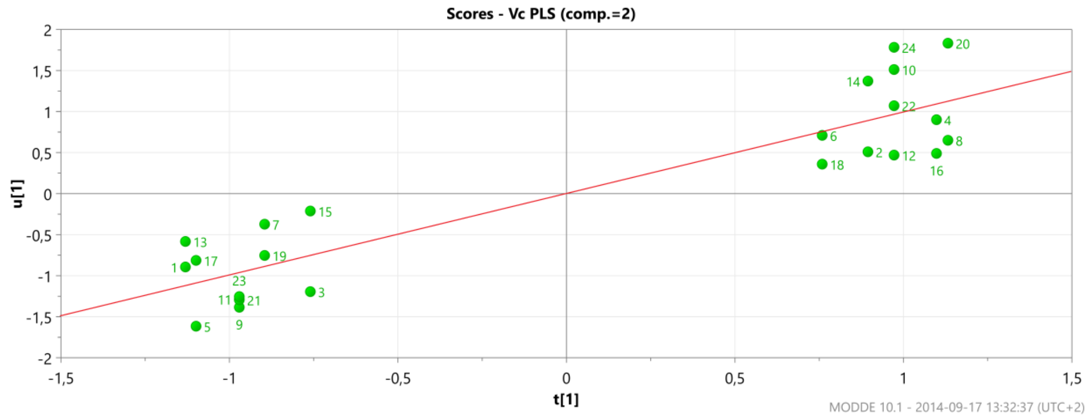

Figure 12. The score scatter plot evaluating the PLS model for the experiments using 7 velocities as response.

To interpret the PLS model the loadings of the second model dimension, wc_2, was plotted against the loadings of the first model dimension, wc_1 (Eriksson et al.,2008). Both Y- and X-variables are presented and the further away from the plot origo a variable lies, the stronger it impacts the model. To evaluate the correlation among the variables, the closeness in the plot is of relevance as well as if its value is positive or negative. This implies that the factor flow is influential for all the responses, however inversely influential for the response groups with the three slowest settling velocities. To further investigate interesting responds, extra reference base-lines can be drawn as in Figure 13. The response groups with settling velocity 18.6 m/h and 0.6 m/h are taken as examples. Orthogonal projections are drawn from each factor onto these two extra reference lines in order to facilitate the interpretation. The further away from the plot origin the orthogonal projection ends up, the stronger the factor. Hence, the dose of anion does not impact the model much at all while the load, coagulant and cation are important for the response in the order mentioned. Since all the responses are positioned very close, similar goes for all of them.

A quick look at the complementary score scatter plot (Figure 12) which displays how well the Y-space (u) correlates to the X space coordinates (t), implies that the statistical model has a slight relationship between factor and response. A scatter plot with all points on a diagonal declares a strong relationship between factors and the responses.

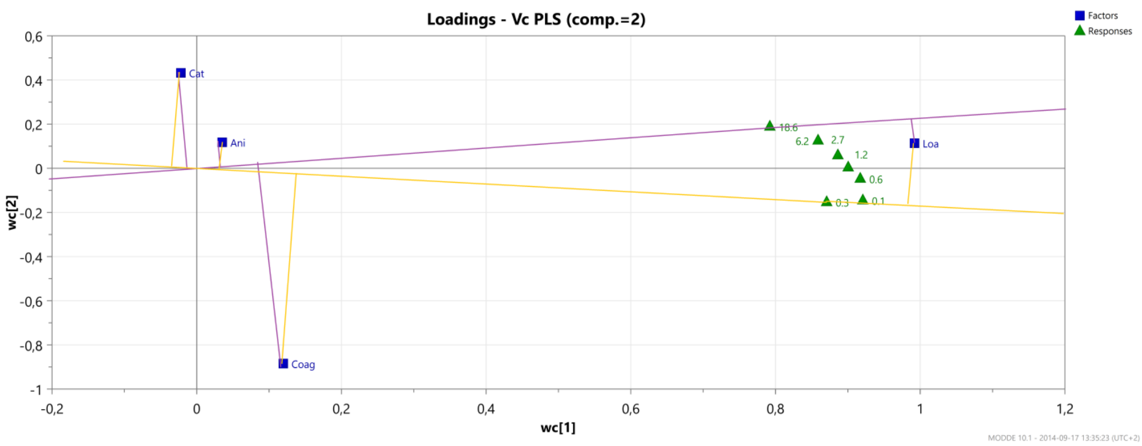

Figure 13. The loading scatter plot of the experiments evaluated with PLS using seven velocities as response.

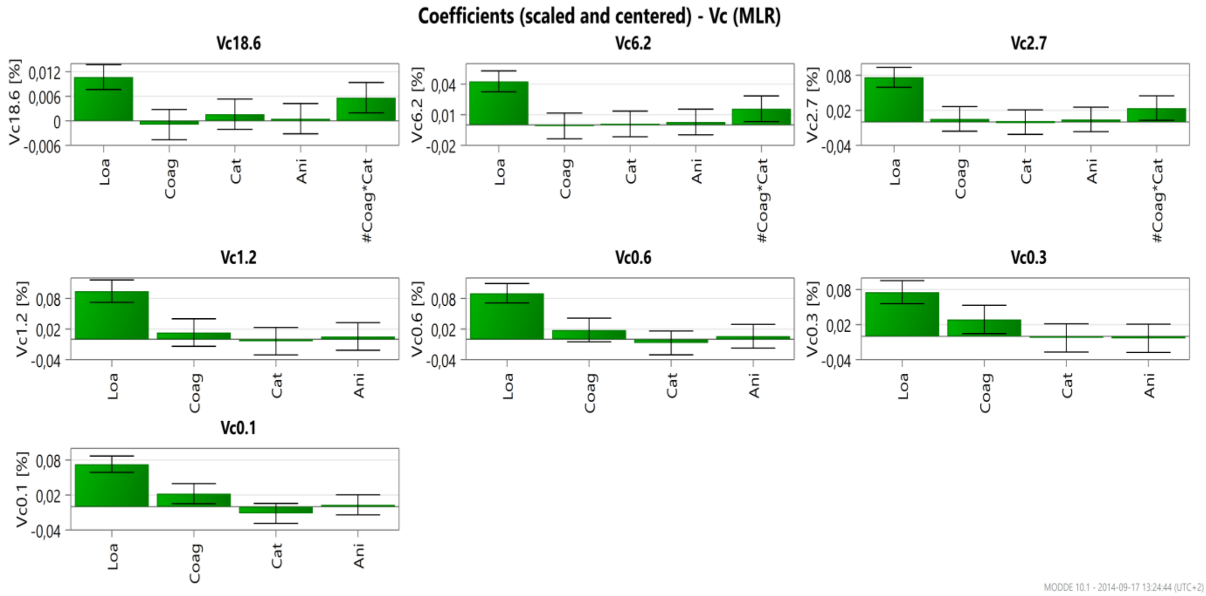

Figure 14. The coefficient plot of the factors describing each settling velocity, terms are scaled and centered to enable comparison of the impact by each term.

4.2.2 MRL Analysis

In order to look more closely at how the different dosages affect the response velocities one by one, a MRL model was evaluated to complement the PLS model. MRL enables to specifically optimize the model for each Y-term, meaning each response which is not possible with PLS. The coefficient analysis, shows that for each response, the dose of both anion and cation has no significant effect (Figure 14). When the spread between the minimum and maximum data value, shown by the "whiskers", deviate around zero the term is not significant. The coagulant is only a significant term for the responses Vc0.3 and Vc0.1. The MRL model can be optimized by square terms and interaction terms. Interaction terms arise when the effect by one factor is dependent on the setting of another. The interaction term between coagulant and cation optimizes the model of the responses Vc18.6; Vc6.2 and Vc2.7. The *coagulant*cation* term is confounded with the *flow*anion* term, but through an educated guess, the *coagulant*cation* term was added to the model in these three cases. Since the PLS model showed that the dose of anion showed to have such very little effect on each response, the guess was that the *coagulant*cation* term represents the significant interaction term.

4.2.3 Effects by Flow and Chemical Dosage

Overall, the flow factor has significant influence on all model responses, meaning the fraction of the total mass that settles within each class is statistically dependent on the size of the flow. The added dose of coagulant affects the particles settling with a very low velocity and the interaction term between the dose of coagulant and cationic polymer seems to affect the particles settling with a fast velocity. The flow has a strong inversely proportional relationship to the settling velocity. Therefore it seems that to endorse a fast settling a low flow is of advantage. As for the added chemicals, an appropriate mix of the coagulant and the cationic polymer is favourable for increasing the fraction that settles faster while the anion seems to not have influence at all. An observation done during performing the experiments was that in some cases extra big flocks were formed that settled quickly and filled the cup and made it difficult to retain all settled particles in the cup when changing. Therefore the actual settled mass may have been greater than what was captured, and measured TSS and VSS of the remnant in the cups might not represent the total settled amount. Changing the cups initially more frequently is recommended.

4.2.4 Effluent Turbidity

An alternative comparison with the PLS model was made with the turbidity online measurements out from the PST 2 as the response. The model had a p-value of 0.001 and both Q2 and R2 just above 0.5. The score plot indicated some correlation between the factors and the response with a few outliers. The factor with the biggest effect was the flow and secondly the coagulant on the turbidity out. A high flow of suspended particles entering the PST also creates a remaining effect on the effluent turbidity. More so it seems that the turbidity also is positively affected by the dose of coagulant. According to the model the dosage of cation has a reducing effect on the turbidity in the effluent as the relationship is inversely proportional.

4.2.5 Residual Phosphate

The residual phosphate concentration in the column at the end of an experiment was looked at. It's an important substrate in the following activated sludge reactors. In addition to being an energy controller the primary clarification may also control the concentration of nutrients. By the reduction of phosphorous though precipitation of phosphate it is an important control mechanism for the rest of the plant. In order for the following treatment steps to work satisfactory there are requirements for nitrogen and phosphorous. For about 100 g of bacterial cell biomass 2.3 g of phosphorous is needed (Metcalf & Eddy, 2014). A concentration of around 11.5 mg/l phosphorous, in soluble or suspended form or as poly-phosphate, incoming to the biological treatment step is favourable (Sehlén, 2014).

Table 8. The residual phosphate concentration in the column with the altering experimental conditions.

	Experimental conditions		**Residual phosphate [µg/l]**	
	Coagulant [mg/l]	Cation [mg/l]	Column 2	Column 2
N1	5	0.5	20	20
N2	5	0.5	289	289
N3	15	0.5	73	73
N4	15	0.5	25	25
N5	5	1.8	392	392
N6	5	1.8	645	645
N7	15	1.8	90	90
N8	15	1.8	0	0
N9	10	1.15	91	91
N10	10	1.15	46	46
N11	10	1.15	0	0
N12	10	1.15	108	108

The residual soluble phosphate concentration in the columns after 2 hours and 25 minutes was close to zero in N1, N4, N8, N10 and N11. The common denominator for these experiments was apart from N1, that the concentration of added coagulant was high or medium (Table 8). In the cases when the remaining amount of phosphate was exceptionally high, N2, N5 and N6, the added dose of coagulant was set to low. In these cases of little precipitation, the ViCA's curves were also relatively far pushed to the right resulting in a smaller fraction of particles settling in the slower classes.

4.3 DEVELOPING A PRIMARY SETTLER MODEL

The ViCA's experiments in this study showed that the sludge had similar properties to secondary sludge because of recirculation of excess sludge. Hindered settling in the ViCA's column was detected in the very first attempt to test the method without diluting the sample. However, for the development of a new PST model in this project, hindered settling was as a first attempt assumed to not occur reflecting an optimally working primary clarifier. The primary clarifier was modeled as a non-reactive 10 layer unit with no hindered settling. The layers are counted from top to down. The water is distributed in the tank model through a feed layer, set to layer number 5, representing a feed 1.4 meter under the surface. Instead of the Vesilind settling model (10), the settling velocity function for each TSS class was set as a constant, the characteristic $v_{s,i}$. The velocity $v_{s,i}$ was given by the ViCA's experiments. The gravitational solid flux J_S, was calculated as:

$$J_S = v_{s,i} \cdot X_m \tag{19}$$

where i is the class. The possibility of a larger flux in a lower level than the one above was taken into account as an exception from the normality, that increased sludge concentrations give lowered flux.

4.3.1 Particle settling velocity distribution

A statistical MRL model produced the basis of the PST MATLAB model. The fraction of TSS given to each class was divided according to the limits, earlier presented in Table 5. A S-function block in Simulink was added prior to the settling tank to create the primary settling velocity distribution (PSVD) and divided the incoming concentration of TSS into the five classes. The PSVD block assigns each class a fraction of the incoming TSS concentration according to the function extracted from the MRL model (Figure 15). The term anion in all the statistical analysis showed little or no significant relationship to the response, therefore this term was disregarded. The cationic polymer term was however kept. A fourth order equation, with the factors presented in Table 9, calculated the fraction of particles settling within each of the five classes as:

$$F(v_S) = A + B \cdot flow \left[\frac{m^3}{day}\right] + C \cdot coag \left[\frac{g}{m^3}\right] + D \cdot cation \left[\frac{g}{m^3}\right] + E \cdot coag \cdot cation \tag{20}$$

where A is a constant; B,C and D coefficients for each factor flow, coagulant dose and cationic dose in named order and E the coefficient for the interaction term. The MRL model for class 4 was not significant and was therefore set to whatever the remaining fraction of particles was after calculating the other classes. The statistical evaluation revealed that the flow is the most important factor for the fraction size of particles settling within class 1 and 2. When it comes to settling class 2 and 3 the dosage of coagulant and cationic polymer are both influential and for settling class 5 the dosage of any chemical seems quite unimportant.

Table 9. The mathematical expression dividing influent TSS into five classes depended on four factors and had these coefficients.

Factors	**Coefficients**				
	Class 1	**Class 2**	**Class 3**	**Class 4**	**Class 5**
A	2.5769	3.9135	29.3718	6.2212	64.734
B	$4.5940 \cdot 10^{-4}$	$4.2735 \cdot 10^{-5}$	$6.6774 \cdot 10^{-5}$	$-8.0128 \cdot 10^{-6}$	$-5.5021 \cdot 10^{-4}$
C	0.475	-0.15769	-0.85769	-0.025	-0.275
D	-1.5385	-0.96154	-4.6154	0.19231	0.19231
E	0	0.11539	0.61538	0	0

The wastewater, after passing the PSVD block entered the PST with 26 defined constituents instead of 21. The five classes of TSS particles were each given a specific settling velocity (Table 10), calculated as the geometrical mean settling velocity within the class boundaries. In the primary clarifier the mass balance of sludge in the 10 layer model was calculated as described in section 3.3. The total flux of suspended solids between each layer in the tank was calculated by flux due to gravity settling and flux due to bulk movement. Above the feed layer the bulk flow is directed upwards and below the feed layer the bulk flow is directed downwards. According to Takács et al. (2001), the higher the concentration the lower the flux, this was taken into account when calculating the gravitational settling flux. The change in concentration of each TSS class in each layer was then calculated as the net flux divided by the height of that layer.

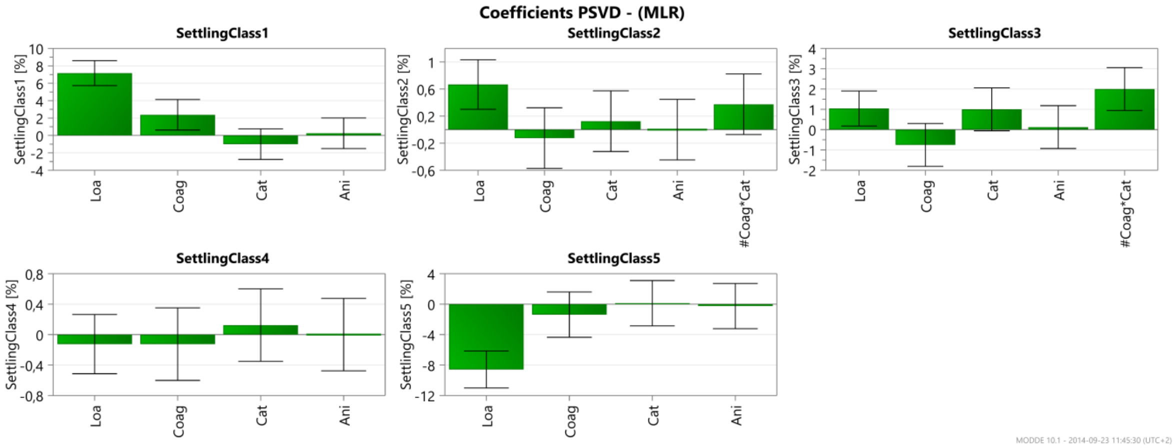

Figure 15. The coefficient plot for dividing the classes, scaled and centered to enable comparison.

The Simulink model can either simulate a dynamic inflow or a constant inflow. In the version of just the primary clarifier, *combiner_3* combines the influent with a likely waste sludge flow from the secondary clarifier and reject water from other process steps of the WWTP. The three factors flow; coagulant dosage and cation dosage is added to the influent. The dose of chemicals was set to differ between morning and afternoon, with a higher load kicking in at 11 am. The effluent from the top layer and sludge outtake from the bottom layer of the PST are stored. This model is possible to incorporate in the bigger model to simulate the entire plant.

Table 10. The characteristic settling velocity for each TSS class (Thiboud[2]).

Class Characteristic Settling Velocity, $v_{s,i}$ [m/day]				
Class 1	**Class 2**	**Class 3**	**Class 4**	**Class 5**
0.096	4.992	13.992	34.008	130.8

4.3.2 Simulation of a typical dynamic influent

A likely influent scenario was simulated in the primary settling model for 609 days (Figure 16). The model was evaluated during the summer months June and July when the experiments where performed, represented by day 396 to 457 (Figure 17). The influent file for the simulation during these months was measured online data from the treatment plant. The dose of both coagulant and cationic polymer was set to low in the morning and switched to high in the afternoon, similarly to the existing control strategy in reality. The average sludge take-out from the primary clarifier was set to 500 m^3/day, which is a likely setting at the real plant.

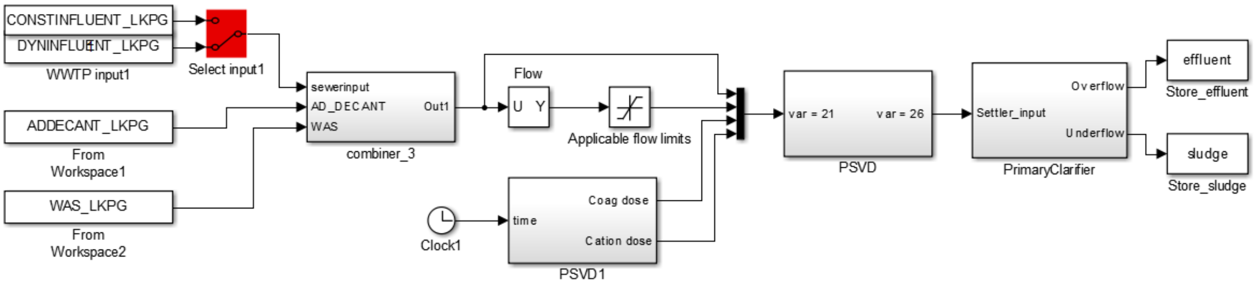

Figure 17. The model of the primary clarifier based on particle settling velocity distribution, presented in Simulink.

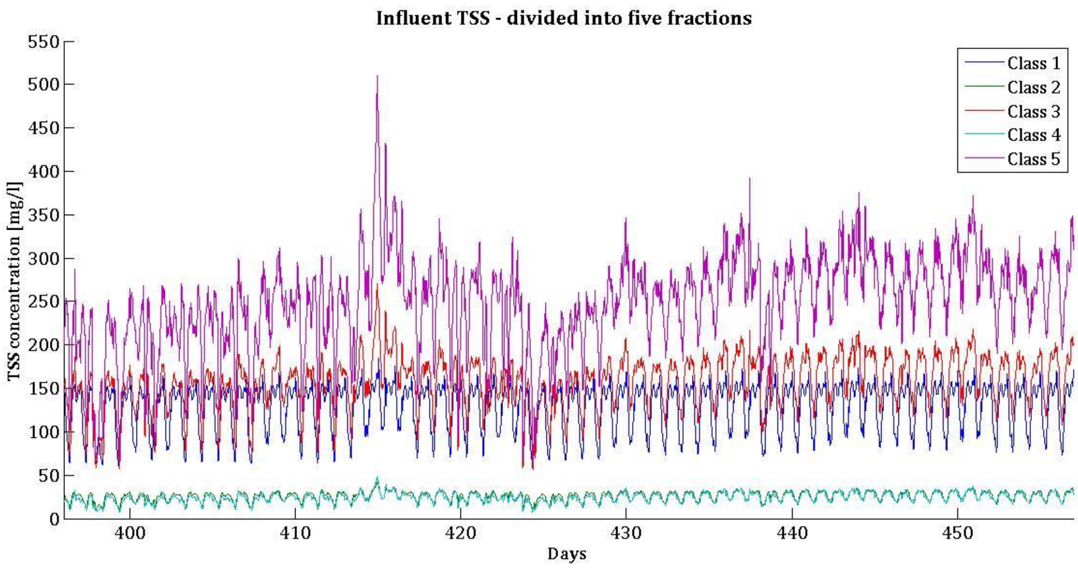

Figure 16. Simulated influent data for June and July, after TSS division in the PSVD function.

[2]Thibaud Maruejouls used the same particle class boundaries primarily in an earlier conducted test series.

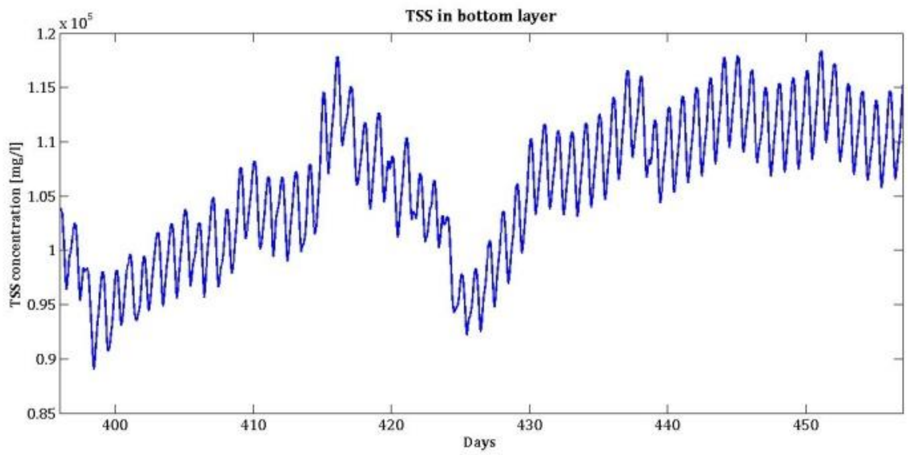

Figure 18. Total solids concentration in primary settler in the bottom layer. Evaluating simulation data June through July.

The distribution of settling velocities for the TSS shows that class 5 solids fluctuate a lot and constitute the largest solids fraction in the influent. Also the class 1 solids represent a large portion of the TSS and is of greater challenge to settle. The variations in sludge flow from the bottom layer as well as the TSS concentration in the effluent can be traced back to the variations in influent (Figure 18). The sludge concentration in the bottom layer, feeding the sludge take-out, should realistically be around 3 to 4 percent. The simulation rather describes a solid concentration around 1000 mg/l, equal to 10 percent (Figure 18).
Simulated TSS data from the months of June and July where compared to online measurements of turbidity during the same time period. The dynamics of the effluent turbidity variation should reasonably coincide with the variation in TSS concentration (Figure 19). The measured turbidity fluctuates with variations due to different days of the week. The influent data used for the simulations does not have any weekly patterns. The daily pattern is however well captured by both simulated data and online measurements. The effluent TSS concentration is very unstable and corresponds closely to a fluctuating influent TSS.

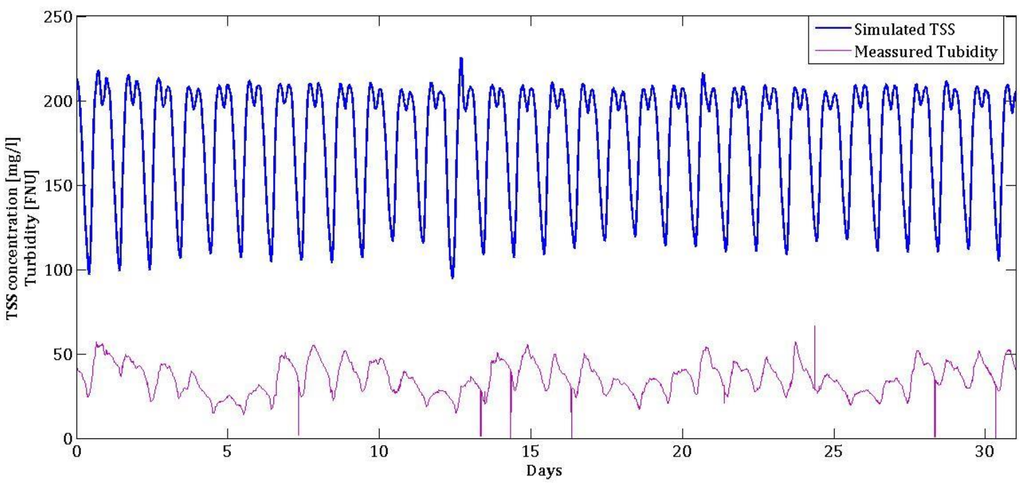

Figure 19. Online measurements of turbidity and simulated concentrations of TSS in the primary effluent during the month of July.

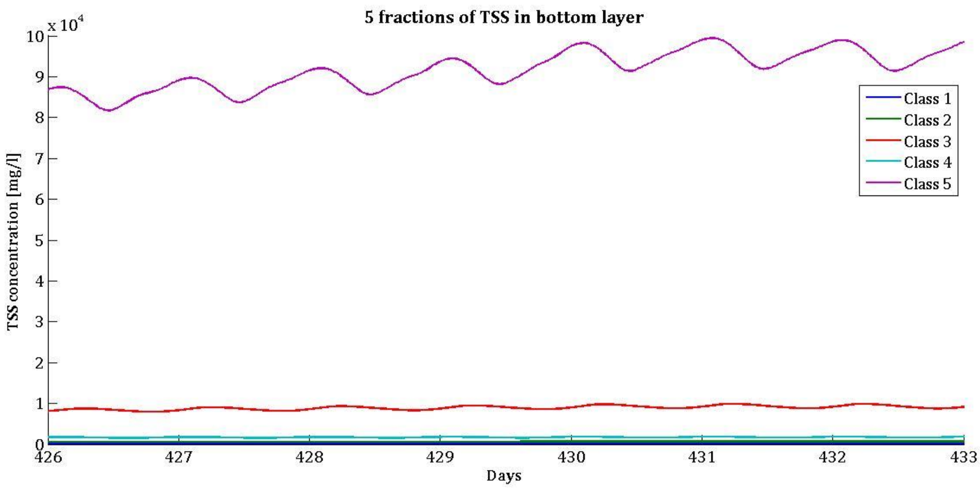

Figure 20. The five fractions of TSS in the bottom layer, evaluating simulation results from the first week of July.

A closer look at the simulation results during the first week of July , presented in Figure 20 and Figure 21, shows the distribution of the TSS classes. During this week (day 426 to 433) the incoming TSS load to the plant was relatively low. Class 5 represents almost the entire amount of settled solids. The contribution from class 3 in comparison to the more fluctuating class 5 is quite steady around 1000 mg/l (Figure 20). Class 3 is the second largest TSS class in the bottom layer of the settler.

At the same time as the fraction of particles belonging to class 1 represents an extremely small part of the settled solids, the fastest settling class, class 5, is oscillating around zero in the effluent (Figure 21). As for the negative values of class 5 in the effluent, this is likely due to an unsatisfactory mean settling velocity for class 5 in the model. Experimentally determined daily average TSS concentration in the effluent was compared to corresponding simulated daily average (average of 24 hours) (Table 11).

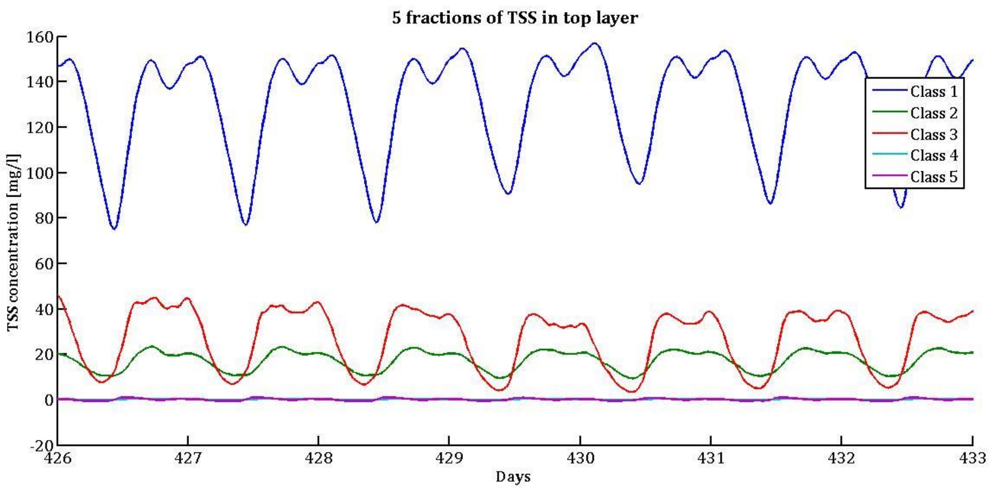

Figure 21. The five fractions of TSS in the effluent, evaluating simulation results from the first week of July.

Table 11. Simulated verses measured data on primary settler effluent TSS.

Date	Experimental TSS data	Simulated TSS data
June 3	130	158
June 11	130	174
June 22	91	178
June 25	130	176
June 30	94	174
July 8	140	174
July 20	88	176
July 23	110	175
July 28	120	176
Average	**115**	**173**

In two other simulations, the dose was constantly set to either high or low to enable a comparison of the impact from the chemical dosage. The same first week of July was used for evaluation. The simulation done at a higher set dose resulted in a slightly higher general concentration of class 5 TSS in the effluent (Figure 22). This goes along with the earlier argumentation in section 4.3.1, that a higher dose of chemicals leads to a greater precipitation of phosphorous which settles slowly and contributes to an increased TSS concentration in the effluent.

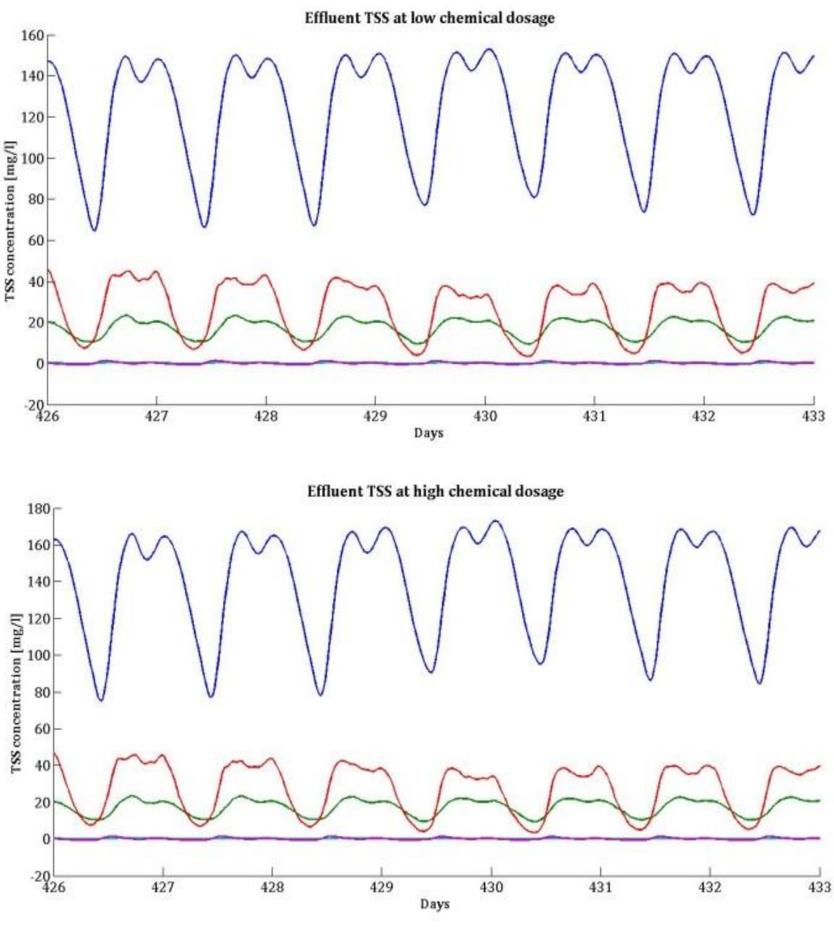

Figure 22. Simulated TSS in effluent divided into the five classes. In the upper panel the chemical dosage was set to low and in the lower panel they were set to high.

4.4 GENERAL COMMENTS

Modeling chemical enhancement in primary settling tanks is important in order to further develop the treatment process and its full potential when utilizing wastewater as a resource. The decision of control strategy should preferably be made through knowledge about the wastewater properties and the solid settling velocities. The hydraulics of the tanks have not been investigated in this project, where it can be assumed that low flow increases the residential time in primary settlers. The flow showed to have a great effect interestingly also in the experiments, a lower flow gave a faster settling velocity distribution. It is however unclear what the factor flow, also named load from start, really states. Probably it represents different types of incoming TSS.

The experiments showed that the residual concentration of phosphate was significantly higher in the cases of a lower added dose of coagulant, ferrous sulphate. This seems to result in a ViCA's class distribution with a greater fraction of particles in the faster settling classes. It seems as if the precipitated phosphate is the greatest contributor to the slower settling particle classes. The MRL model (Figure 15) showed the same tendencies, with the dose of coagulant being a relatively large significant term describing the fraction of particles settling within class 1. The interaction term between coagulant and cationic polymer shows that an increased fraction of particles settling within class 2 and 3 is dependent on the set dose of coagulant in combination with the dosage of cation polymer. The effluent turbidity increased with added coagulant dose while the turbidity decreased with a larger dose of cation. These results follow the same argumentation as for the residual phosphate concentration. A high flow of suspended particles entering the PST gave generally a high remaining turbidity in the effluent. As for the added chemicals, an appropriate mix of the coagulant and the cation ic polymer is favourable for increasing the fraction that settles faster while the anionic polymer seems to have no influence.

The class boundaries used to create the settling velocity distribution should be calibrated through better matching of simulated data with existing measured data. When the optimal model for the time period June/July is found, the MATLAB/Simulink model should be further testified though confrontation with new data series using cross-validation (Ljung & Glad, 2011). How the occurrence of hindered settling in the primary settlers can be implemented in the model should be further investigated. Since the ViCA's method assumes flocculent settling the method needs to be re-evaluated for cases where for example bio-sludge is re-circulated.

4.4.1 Practical Implementation

The primary settler model can advantageously be used for simulating altering chemical dosage with varying dynamic influent according to different scenarios. More knowledge about the capacity of sludge withdrawal from the primary clarifier can be provided and how the optimal chemical dosage is set to maximize settling. Such simulations can be of benefit when deciding on a new control strategy for the plant. If the goal is to maximize the sludge outtake for biogas production for example this model can provide the sludge flow dimensions that can be expected. When maximizing the sludge outtake also following steps such as dewatering, digesters and gas chambers must be dimensioned accordingly. This model will give a hint to what dimensions are needed and what possibilities exist.

5 CONCLUSIONS

The concluding remarks in this report can be stated as:

- The TSS components are of great importance to the settling properties in the primary settlers, having a seemingly large effect on the settling velocity distribution, in this project evaluated in terms of flow.
- As for the model, flow could be used as a state variable to describe the difference between morning and afternoon samples. The components of TSS in the morning differ from the afternoon.
- The fraction that settles within the slower settling classes decreases when the flow entering the plant is low.
- The addition of return sludge from other plant processes has great impact on the primary sludge. A large addition of secondary bio-sludge seems to increase the overall settling velocity which was seen in the collective results from the morning samples. Since the influent TSS to the primary clarifier was more or less the same during the day but the plant influent TSS lower in the morning, the equalizing factor must be the re-circulation of sludge.
- In order to optimize the primary clarifiers it is critical to look at how to increase the settling velocity for the class of particles settling very slowly, class 1. It seems that the slowest class of suspended particles is increased as more coagulant is added to the wastewater due to precipitation of soluble components. The classes settling a bit faster, class 2 and 3, are then increased if also a cationic polymer is added to form the particles in heavier flocks. The particles within class 4 and 5 seem to settle fast regardless the enhancement by chemicals.

Ultimately, it can be concluded that the principles behind the resulting model works in order to simulate credible data and that the experimental ViCA's equipment can be used to find the settling velocity distribution. The occurrence of hindered settling was in itself a noteworthy result. Using dilution was a solution for the analysis method to avoid hindered settling in the column. The effect on the settling caused by dilution and how to implement hindered settling in the model should be further investigated.

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APPENDIX

In the experimental analysis the following equipment were used:

2 x ViCA's experimental set-up, column with support.

4 x ViCA's settling cups

2 x elastics (keeping the column up-right)

2 x stopwatch (measuring time steps)

2 x ViCA's spread sheet (registration information)

1 x 5 liter beaker (for sampling)

1 spatula (for homogenization)

1 single stage vacuum pump – Ultimate Vacuum pressure: 10 Pa.

2 x connecting pipes and pipe connections

1 Erlenmeyer filtration 1000 ml (pump protection)

4 x 100 ml beakers (for emptying cup contents)

2.0 µm filters (for TSS and VSS analysis)

Filter holders